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COLUMBIA RIVER ENTRANCE CHANNEL DEEP-DRAFT VESSEL MOTION STUDY. (U)

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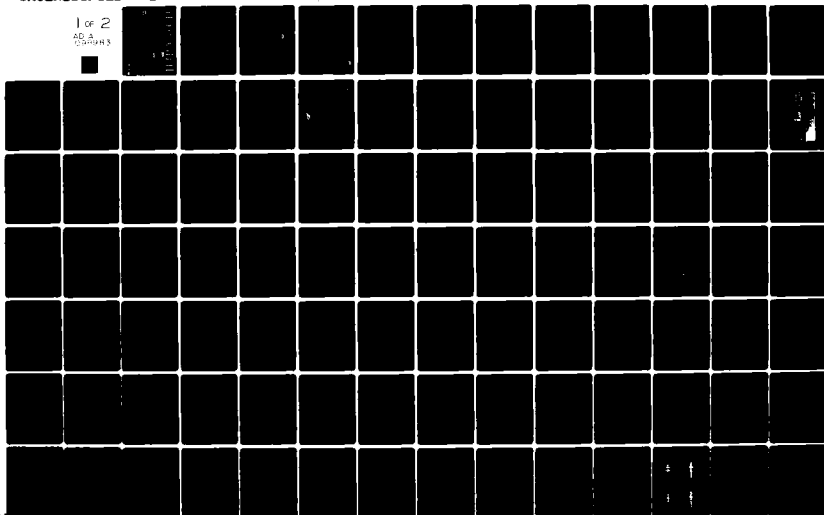
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COLUMBIA RIVER ENTRANCE
CHANNEL DEEP-DRAFT VESSEL
MOTION STUDY

FINAL REPORT

AD A098983

PREPARED FOR

DEPARTMENT OF THE ARMY
PORTLAND DISTRICT, CORPS OF ENGINEERS
UNDER CONTRACT
NO. DACW 57-78-C-0028

BY
SHEN WANG
CHRIS BUTCHER
MICHAEL KIMBLE
GLENN D. COX

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A prototype ship motion monitoring program was initiated by the Portland District U.S. Army Corps of Engineers to provide design criteria for the entrance channel at the mouth of the Columbia River. The contractor's field team boarded deep draft vessels bound to or from the Columbia River and measured vertical acceleration (heave), pitch, roll, yaw, and position as the vessels transited the 5-mile entrance channel. Twenty-nine vessels were monitored in the period May 1978-March 1979, and twenty-four in the period October 1979-April 1980.			

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The final report details the field work data reduction processes, analyses, and results. The raw data is used to calculate vertical motions at the bow, stern, and side of the vessel, and the horizontal motion as the ship transits the entrance. This information is evaluated with respect to environmental conditions and the channel. Results of statistical analyses are shown for characteristics of individual transits, and long-range entrance usage.

Appendices A-K contain the tabulated and plotted motion data, environmental conditions, ship motion variables, and other information collected.

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Daunt, Mr. Dick Smith and Mr. Warren Beebe of Chevron Shipping Co.; Mr. Steve Mandle, Capt. McKimney and Mr. Phil Lutes of Weyerhaeuser; Dr. Peter Fischer and Capt. Tony Haydon of Matson Navigation Co.; Capt. T. Ishikawa of Mitsui OSK Lines, Mr. Steve Blydenburg and Mr. Carter Meyer of Williams Diamond and Co. agents for Mitsui OSK Lines; Mr. D. Nihei of Kerr Steamship Co., Inc. agent for K-Lines; Mr. Jeff Hall and Mr. Phillip Van Oppen of International Shipping Co. Inc. agents for Y-S Lines; Capt. Miyamori of Matson Agencies Inc. agent for NYK Lines; Capt. Nishikawa, agent for Japan Lines; and Mr. John Reilly of Montreal Shipping Company Limited, agent for Act Maritime.

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GLOSSARY OF TERMS

- Amplitude - The maximum value of the displacement of a wave or the periodic movement of a ship from the mean zero position.
- Bilge - The curved portion of a ship section, where the side hull meets with the bottom.
- Bow and stern - The forward and aft parts of a ship, respectively. Geometrically, they may be referred to as FP (Forward Perpendicular) and AP (After Perpendicular), respectively. The forward perpendicular is the line perpendicular to the keel line through the intersection of the ship design water line and the foreside of the bow. The after perpendicular on the other hand, is the vertical line through the intersection of the design water line and the after side of the stern contour or the straight portion of the rudder post for ships possessing a well-defined rudder post.
- Broaching - A ship turning broadside to the waves.
- CG - Center of gravity. To describe the center of gravity of a ship, the following two terms are used:
LCG - longitudinal center of gravity of a ship, measured from AP
VCG - vertical center of gravity of a ship, measured from keel.
- Course - The intended horizontal direction of travel of a ship.
- Course Made Good - The direction of a point of arrival from a point of departure. In the present case, it is defined as the direction corresponding to that portion of the recorded track for which the ship holds a steady course.
- Displacement - The weight of the water displaced by a ship; the weight of a ship. Also used to denote the movement of a ship in any given mode.
- DWT - Deadweight tonnage; the weight of cargo, stores, and bunker fuel which a ship can carry.

- Effective Lane Width** - The total lane width requirement for a ship passage; a combination of the ship's track width and the additional cross-channel projection of the ship due to yaw.
- Excursion** - Total movement up or down at any particular location of a ship in any particular direction.
- Bow excursion** - total vertical movement due to the combined motions of pitch and heave at the bow
- Stern excursion** - total vertical movement due to the combined motions of pitch and heave at the stern
- Side excursion** - total vertical movement due to the combined motions of heave and roll at the port or starboard side, amidships
- Sideways excursion** - horizontal movement of a ship; sway.
- Heading** - The horizontal direction in which a ship actually points or heads at any instant.
- Period of Encounter** - Apparent period of waves as observed from a moving ship.
- Port and Starboard** - The left and right side of a ship, respectively.
- Principal Dimensions** -
- Length** - two lengths of a ship are normally used:
 - LOA - length overall, the overall length of a ship from bow to stern
 - LBP - length between perpendicular, the distance between FP and AP, the characteristic length normally defined by a naval architect.
 - Beam** - the maximum width of a ship or the width amidships
 - Depth** - the vertical distance between keel and the main deck
 - Draft** - the depth to which a vessel is submerged.
- Ship Motions** - Without any constraint, a ship moves in six degrees of freedom in a seaway:
- Surge** - bodily movement of a ship in the fore and aft direction
 - Sway** - bodily movement of a ship in a direction normal to the heading
 - Heave** - linear oscillatory motion in the vertical direction

Roll - angular oscillatory motion about a ship's longitudinal axis
Pitch - angular oscillatory motion about a ship's lateral axis
Yaw - angular oscillatory motion about a ship's vertical axis.

Vessel

Penetration - The maximum depth of submergence of a vessel when it is in motion.

Vessel

Track or

Trajectory - The horizontal path described by the center of gravity of a ship during a transit.

1.0 INTRODUCTION

This study is a part of the overall program for the Columbia River channel development directed by the U.S. Army Corps of Engineers, Portland District. The objective of this study is to assist the Corps to validate the channel design assumptions by directly measuring the motion characteristics of deep-draft vessels as they transit through the entrance channel. The general location of interest for the present study is shown in Figure 1.

The study consists of two phases. The first phase of the study was initiated in November 1977 and completed in September 1979. The actual field measurements in this phase covered one late spring season from May through June of 1978 and one winter season from November 1978 through March 1979, providing data of ship motions for 29 ship-transits. The second phase started in late September 1979 and the field operation was extended to early April of 1980 to include 24 more ship-transits. Analyses of the first phase data have been presented in the Phase I report [1]. The present report summarizes the results of analysis for both Phase I and II data and thus represents the final report of the study and supersedes the Phase I report.

In conjunction with the study, a wave measurement program was initiated with the cooperation of the U.S. Army Coastal Engineering Research Center (CERC) and the Pacific Marine Environmental Laboratory of NOAA. During the field operation period of the Phase I study (May 1978 to March 1979), three sets of wave data were collected simultaneously in conjunction with the ship motion data measurements. Wave data were collected in conjunction with all but four of the ship transits during the Phase II study. The wave measurements were additionally enhanced by a radar-image program to provide information on the direction of the wave field beginning at the latter part

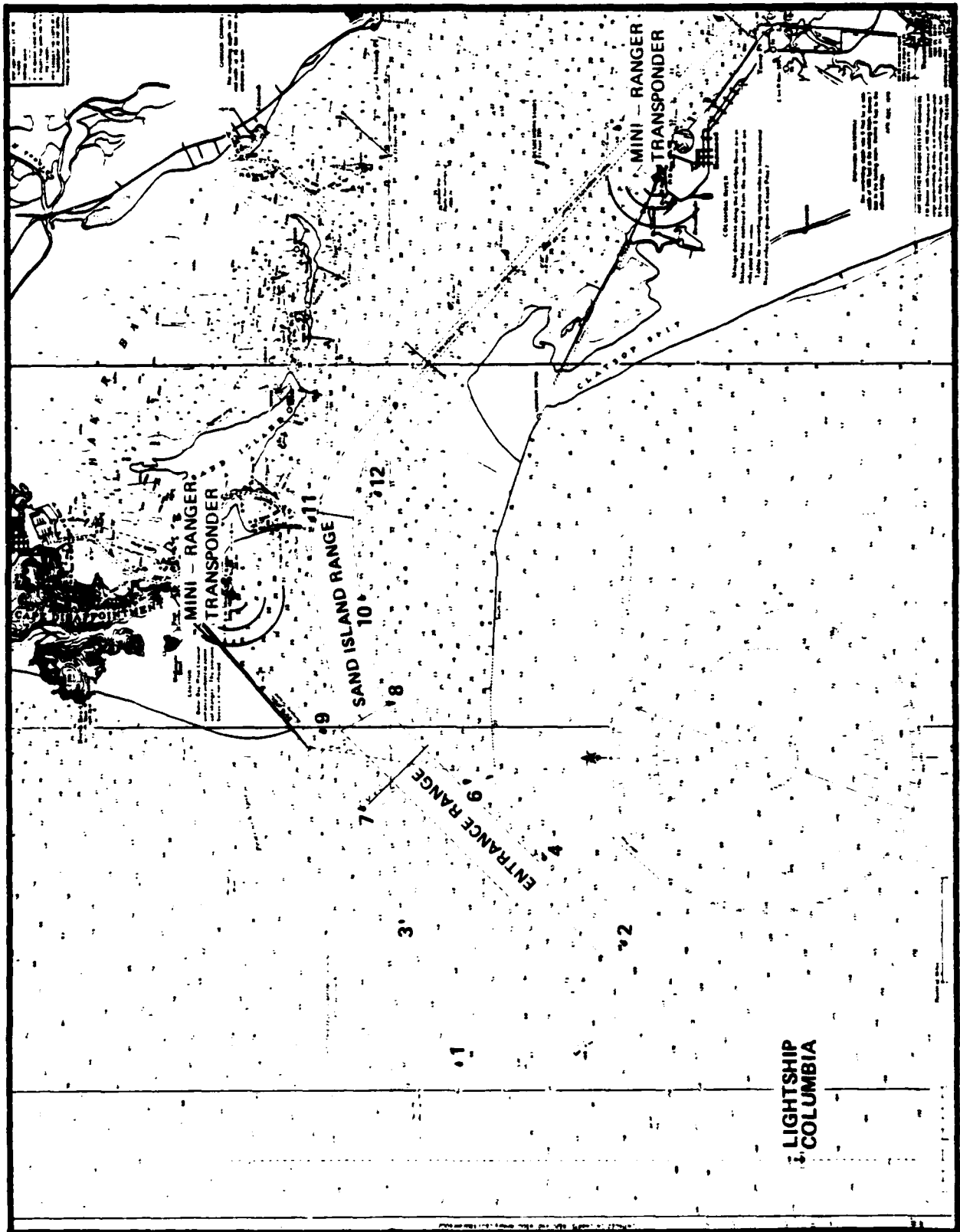


FIGURE 1 - COLUMBIA RIVER ENTRANCE

of the first phase study. As a part of the system, a time-lapse camera to photograph a Raytheon radar scope was included and installed at Cape Disappointment, Washington. Simultaneous recordings from wave gauges and radar image with ship motion measurements were in principle intended in the entire second phase.

The application of vessel motion analysis to channel design is a multi-loop process. As indicated by the block diagram shown in Figure 2, a ship is subjected to environmental disturbances (wave, current, wind, etc.), ship-channel interactions and the pilot control to yield six degrees of freedom motions. Once the vessel motion characteristics become available, the design process may proceed and the channel particulars can be evolved. As a result, however, the ship-channel interactions will be modified and the pilot command may be

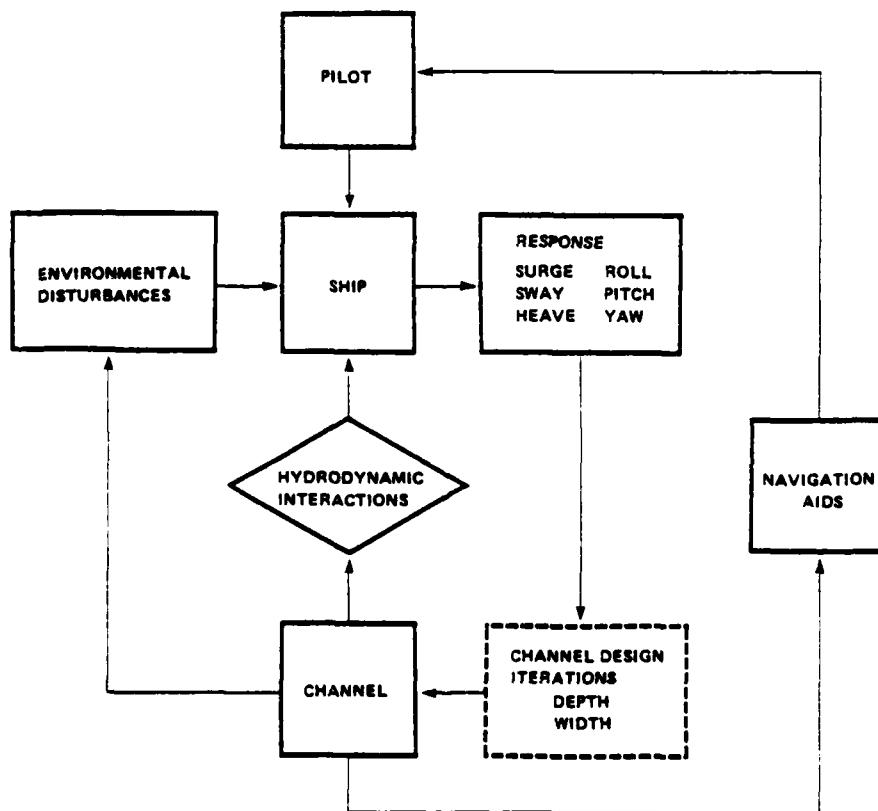


Figure 2 Iteration Procedure for Channel Design Analysis

affected, and thus an optimum design must be accomplished through iteration procedures.

The interaction between vessel motion and channel design has become a challenging problem to scientists and engineers internationally. For instance, a symposium specifically on the navigability of constraint waterways was jointly sponsored by the Permanent International Association of Navigation Congresses (PIANC) and the International Association for Hydraulic Research (IAHR) and held in Delft, the Netherlands, 1978 [2]. A summary of the papers presented at the symposium has been reported by Abraham and Lepetit [3]. In the United States, two conferences related to navigation channel design were held at Vicksburg, Mississippi, both sponsored by the U.S. Army Corps of Engineers [4, 5].

The interest in this problem in this country was actually initiated several years ago when a Task Committee on Ship Channels was formed by the Committee on Ports and Harbors of the Waterways, Harbors and Coastal Engineering Division of the American Society of Civil Engineers (ASCE) to investigate the engineering of safe, adequate and economic channels and maneuvering areas for large sea-going vessels. A progress report of the Task Committee was presented at the ASCE National Transportation Engineering Meeting held at Boston, Massachusetts, 1970, and altogether seven reports were planned to be published subsequently in the ASCE journal [6].

Not many previous studies exist in applying full-scale measurements of vessel motions to channel or waterway design. Naval architects have utilized shipboard measurements to evaluate motions and stresses for a given type of vessel under various sea conditions. For instance, Bledsoe et al. [7] analyzed three Dutch destroyer motions using their shipboard recorded trial data, and Jasper [8] statistically interpreted the measured motion and stress data for several U.S. naval vessels.

More recently, a very sophisticated instrumentation system was installed on board the American container ship *Sea-Land McLean* and continuously recorded motions, stresses and the bending moment data for several years [9]. Due to governmental and industrial interest in these programs long term support was made available which is not ordinarily the case. Also, the sensors and instrumentation used in these programs were custom designed for permanent installation aboard a particular vessel.

The purpose of the present measurement program is somewhat different, as the measurements in this program must deal with a number of different vessels but at one location, a given entrance channel. Consequently, the instrumentation required in this program must be portable and easy to install and remove from vessel to vessel.

The report is organized as follows. The instrumentation system is detailed in Section 2. Field operations and procedures are outlined in Section 3 followed by a summary of the basic data consisting of generalized voyage descriptions and vessel characteristics in Section 4. A detailed discussion of environmental conditions at the study site together with the environmental conditions actually encountered during the field study is presented in Section 5. The methodology and procedures to process and analyze the recorded data are then given in Section 6. Time history plots of all motion variables together with the vessel track trajectory for each voyage are summarized in Appendix A. A statistical analysis of the recorded data has been conducted and some statistical correlations have been presented in Sections 7 and 8. Spectral estimates for ship motions and wave data are summarized and correlated in Section 9. The significant results derived from this analysis are then summarized in Section 10.

The repository for the raw data recorded on each voyage is the Portland District Army Corps of Engineers. All inquiries

2

concerning the raw data should be addressed to the following:

Advance Engineering Unit
Portland District, U.S. Army Corps of Engineers
Post Office Box 2946
Portland, Oregon 97208

2.0 INSTRUMENTATION

2.1 INTRODUCTION

The Ship Motion and Positioning System, SMPS, was developed to monitor and record motion characteristics of deep draft vessels transiting through the entrance channel of the Columbia River. Motions of particular interest are pitch, roll, heave, yaw and position of the ship in the channel. The SMPS is equipped with instrumentation to monitor and record pitch, roll, vertical acceleration, ship's heading and position. Heave and yaw motions cannot be measured directly, but are analytically determined from the vertical acceleration and ship's heading, respectively. A brief discussion of the design constraints, system description, and individual components of the SMPS is given in the following sections.

2.2 DESIGN CONSTRAINTS

Due to the transfer of the SMPS from ship to ship, the shipboard environment, and the data acquisition requirements, several constraints were imposed upon the design of the system. These constraints include compact size, portability, capability of utilizing the ship's power system without interference to or from the shipboard environment and the ability to rapidly monitor and record large quantities of data.

Physical Size

The SMPS was designed to set up and operate in the bridge area of the ships. Because space is often limited in the bridge, the SMPS had to be compact and adaptable to the space available.

The navigational chart table was usually large enough to accommodate the SMPS, but on occasion the components of the SMPS had to be physically separated. This problem was overcome by

utilizing long power and interconnecting cables between components. The minimal space needed to set up the SMPS is a surface area of approximately 5.5' x 2.5'.

The nature of the field work necessitated shipping the SMPS via commercial air freight and automobile. In order to meet this need the individual components and accessories are provided with foam lined fiberglass shipping crates. The crates are approximately 2' x 2' x 4' and are easily handled by two people. The entire SMPS can be shipped in six crates weighing a total of approximately 400 lbs., thus making the system easily transportable.

Shipboard Environment

A major concern in the design and utilization of the SMPS was the problem of interference to or from the ship's electronics and/or radar system. Electrical interference was minimized by using shielded cables and grounding all instrumentation. In addition, RC filters (-3 db 60 Hz) were used on each of the analog multiplexer channels to filter unwanted electrical noise. Since the data of interest are at much lower frequencies, no net effects of filtering on these data are considered.

Radar interference between the positioning system and the ship's radar was not a problem. The positioning system has an operating frequency of 5480-5570 MHz while the ship's radar system operates at either 3050 ± 10 MHz or 9375 ± 30 MHz depending upon the desired resolution.

One problem encountered was with the ship's power supply. The SMPS is dependent upon the available power in the wheelhouse of the ship. American flag ships have standard 110 volts while foreign flag ships may vary from country to country. A 100 volt and 220 volt system was encountered on board Japanese and Norwegian ships, respectively. Because the SMPS uses 110

volts, it was necessary to obtain a 220-110 volt transformer and European electrical plugs to adapt to the European ships. No changes were necessary for the Japanese ships.

Data Recovery

The most imposing constraint upon the SMPS was the need to monitor and record the data at a rate of 5 scans/second for a period of approximately 30 minutes. The data must be recorded five times per second so that the vertical acceleration data will lend itself to the necessary numerical analysis to compute the heave. The data acquisition system was designed with this in mind and is equipped with a tape recorder capable of storing such large quantities of data.

2.3 SYSTEM DESCRIPTION

A photograph and schematic block diagram of the SMPS is shown respectively in Figures 3 and 4. The schematic diagram illustrates the operational set up of the system and the flow of data from the sensors to the data recorder.

Operation Profile

The Hewlett-Packard 9825A calculator controls the SMPS. Once the system hardware is configured and powered up the data acquisition program is loaded into the calculator. Data acquisition is then initiated by running the program. Data are read from the mainframe at a predetermined sampling rate and stored in a buffered area of the calculator memory. The procedure continues until the buffer is full, at which point the data are sent to the Qantex Tape Drive for storage on magnetic tape. The system operation is fully automatic during this process and continues to read and write data until the user issues a stop command from the calculator.

- 1 CENTRAL CONTROLLER
- 2 DATA PROCESSOR
- 3 TAPE RECORDER
- POSITIONING SYSTEM
- 4 CONSOLE
- 5 REFERENCE STATION - 1 OF 2 ON SHORE
- 6 MOTION SENSOR
- 7 SHIP'S HEADING SENSOR
- 8 POWER INVERTER

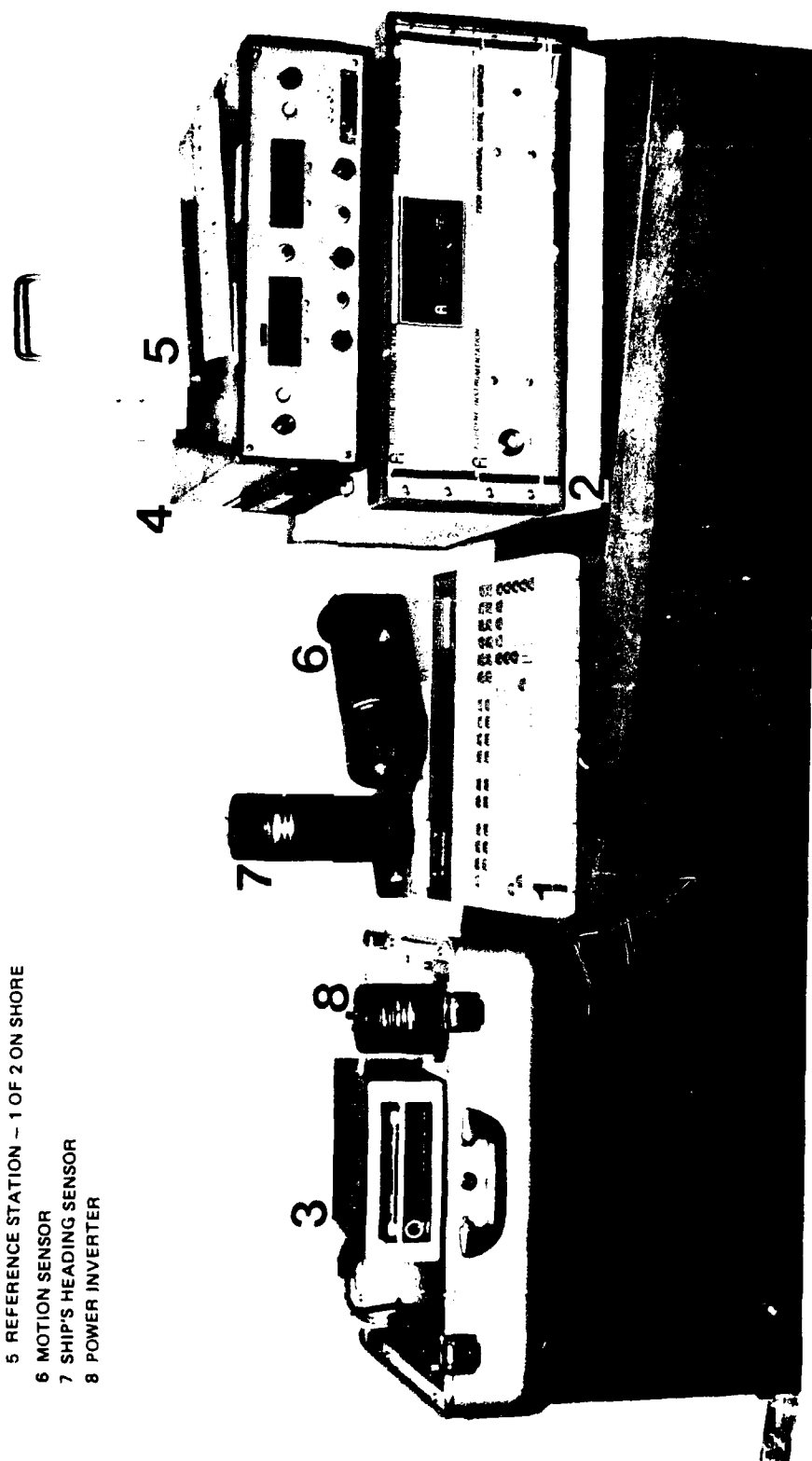


FIGURE 3 SHIP MOTION AND POSITIONING SYSTEM

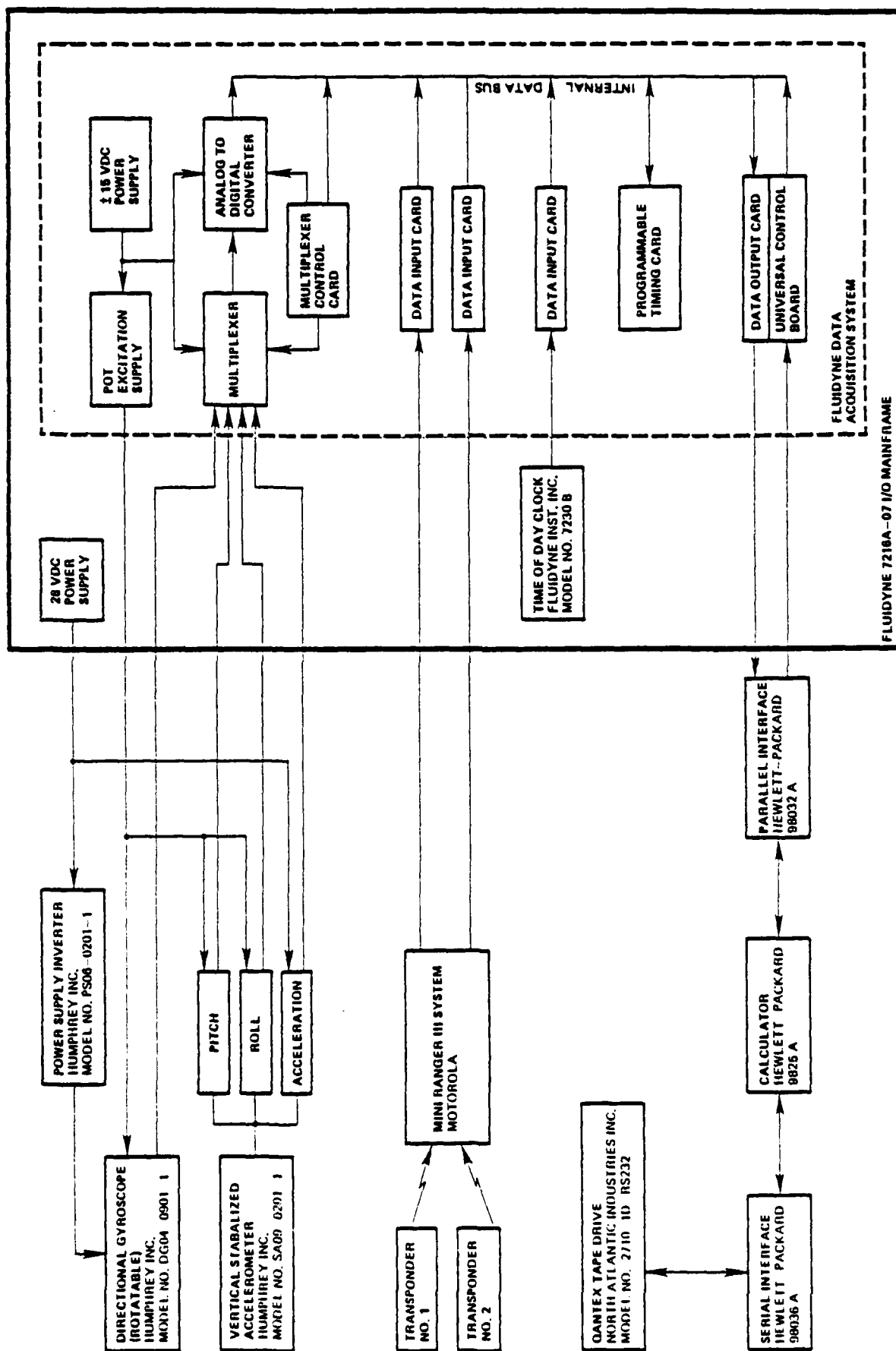


FIGURE 4 - BLOCK DIAGRAM OF SMPS

Features of the System

The SMPS is capable of sampling and recording data at rates from 5 scans/second to 1 scan/hour (software controlled). At the maximum scan rate of 5 scans/second, data can be recorded continuously for approximately 35 minutes. In addition to recording the data, the data is continuously displayed in real time on the calculator LED display. Also, a hard copy of one scan of data may be obtained from the calculator strip printer when the user issues a print statement. The print statement must be used cautiously as it will interrupt the continuous data recording.

Data management and editing are facilitated by the versatility of the Qantex Tape Drive. Once the data is recorded a file mark is placed at the end of data. The data can then be read back through the calculator for editing, analysis or transfer to another storage medium.

Perhaps the most important feature of the SMPS is its portability, adaptability, and ease of set up and operation. The entire system can be set up and operating within one hour. Anyone with a general knowledge of electronics and computers can easily learn to operate the system. Instrument specifications are included in Appendix B.

2.4 SYSTEM COMPONENTS

Following is a description of the individual components of the SMPS. Technical specifications are presented in Appendix B.

Central Controller - Hewlett Packard 9825A

The HP9825A is a programmable calculator with a memory size of 16K bytes. The programming language is Hewlett-Packard Language, HPL. Features of the HP9825A include a digital

cartridge, LED display, strip printer and I/O capabilities. In addition to the above features the following options have been included for use with the SMPS: General I/O-Extended I/O ROM, String-Advanced Programming ROM, 9885M Flexible Disk Drive ROM, HP98032A 16 Bit Parallel interface and HP98036A Serial I/O Interface.

The calculator can operate on any of the following line voltages: 100, 120, 220, 240 volts. Dimension and weight of the calculator are approximately 5" x 15" x 20" and 20 lbs.

Data Processor - Fluidyne 7216A-07 I/O (Mainframe)

The Fluidyne Data Processor is a custom designed instrument. Included within the mainframe are the time of day clock, 28 VDC power supply for the motion and heading sensors, multiplexer and analog to digital converter for the analog data signals, data input cards for the digital data signals, and a programmable timing card.

The mainframe has 16 I/O slots for analog and/or digital data. Only 7 of the slots are utilized in the SMPS, 3 digital and 4 analog. Digital signals are input directly to the data input cards while the analog signals are routed through the multiplexer and analog to digital converter. Only 4 multiplexer channels are used, although there are 16 available. The 4 channels that are used are equipped with RC filters to reduce electrical noise. The programmable timing card controls the rate at which the 7 data channels are sampled. The sampling rate is adjustable from 5 scans/second to 1 scan/hour.

There are two external connections to the mainframe, both of which require 110 volts. One source is for the cooling fan while the other is to power the electronics. The electronic circuit cards are powered by an internal 5 VDC, 6 A regulated power supply. The mainframe is the largest and heaviest

component of the SMPS. The approximate size and weight are 11" x 20" x 20" and 70 lbs.

A complete loss of data occurred once throughout the project, on Voyage 49, and was due to a faulty electrical component within the data processor.

Tape Recorder - Qantex Model 2710-1D-RS232

The Qantex Tape Drive is a portable program loader/logger equipped with a Hewlett Packard compatible RS232 interface. Data are stored on a 3MDC300A Data Cartridge which has a 4 track storage capacity of 2.5 million bytes or 625,000 bytes per track. The above features, HP compatability and long, uninterrupted recording capabilities, were instrumental in choosing the Qantex for the SMPS system. The Qantex is remote controlled by the HP9825A. Commands can be issued directly via the keyboard of the HP9825A or through a program.

The Qantex is self-contained in an aluminum carrying case making it ideal for field use. Overall size is 21" x 17" x 7.5" with a total weight of 29 lbs. A 110 volt power source is needed to operate the Qantex.

Positioning System - Motorola Mini Ranger III

The Motorola Mini Ranger III is a positioning system based on the principle of pulse radar. Position of the ship is determined relative to two fixed reference stations. Operational range of the system is limited by line-of-sight between the radar transmitter and the reference stations, this distance being typically 20 nautical miles depending on the elevation of the radar transmitter and reference stations. With proper calibration, the range measurements are accurate within ± 10 ft.

Components of the positioning system include the range console, receiver-transmitter and two reference stations. The range console and receiver-transmitter were located shipboard while the reference stations were permanently positioned one at either side of the mouth of the Columbia River. The reference stations are interrogated by the receiver-transmitter and the ranges computed from the time delay in their response to the receiver-transmitter. Ranges are updated every second and are displayed on the range console for the user to observe. The ranges are later trilaterated to compute the actual position.

Reference stations are coded to allow identification of the ranges. The range console has the capability to interrogate up to four different reference stations, although only two can be interrogated at one time.

The receiver-transmitter is interfaced to the range console by means of a 100 ft cable. The range console operates on either 110 or 220 volts and provides a 24-30 VDC supply to the receiver-transmitter. Each reference station includes a 100 ft power cable and a power inverter which converts 110 VAC to the required 30 VDC.

The range console cabinet is 18' x 5.5" x 17" and weighs 30 lbs. The receiver-transmitter is 6.25" x 6.5" x 9.25", plus antenna (9" long), and weighs 5 lbs. The reference stations are 5.5" x 6.5" x 10.5", plus antenna (10.5" long), and also weigh 5 lbs. each. The interconnecting cable between the range console and receiver-transmitter is 100 ft long with a diameter of approximately 1" and a weight of approximately 40 lbs.

Position data was unavailable on 4 of the 29 voyages in Phase I (Voyages 3, 8, 14, 25). Two of these occasions were attributable to reference station failures, one to a reference station power supply failure and one to a range console power

supply failure. In the second phase, position data was unavailable on 3 of the 24 voyages (Voyages 41, 45, 49). Two of these occasions were again attributable to reference station failure and the third was due to the failure in the Fluidyne data processor.

Motion Sensor - Humphrey, Inc., Model SA09-0201-1

Ship motions--pitch, roll and vertical acceleration--are all measured by a Humphrey Vertical Stabilized Accelerometer, Model SA09-0201-1. The instrument consists of a vertical stabilized gyroscope with an accelerometer mounted on the inner gimbal and potentiometers on the inner and outer gimbals for measurement of pitch and roll. The accelerometer is mounted such that it is always vertical; therefore, only vertical accelerations are measured regardless of the orientation of the ship (or instrument).

The potentiometer outputs are proportional to the angular displacement about the pitch and roll axes. The mechanical limits of the gyroscope are $\pm 85^\circ$ about the pitch axis and 360° about the roll axis. The maximum pitch and roll electrical displacements are $\pm 50^\circ \pm 2^\circ$ with a resolution of 0.2° . Linearity is 0.5% of full scale. The accelerometer has a range of ± 2.0 G with an output sensitivity of 2.5 V/G. Accuracy of the accelerometer is $\pm 0.1\%$ of full scale.

A 28 VDC power supply is used to power the motion sensor. Voltage to the accelerometer is internally regulated at 24 VDC. Voltage to the spin motor and erection system is regulated through an internal inverter at 115 VAC, 400 Hz, single phase. The instrument is cylindrical in shape and amazingly compact with an overall length of 10" and a diameter of 3.13". Maximum weight is 5 lbs. A mounting bracket is included with the instrument.

Pitch, roll, and vertical acceleration data were unavailable on two voyages throughout the project (Voyages 38 and 49). On one occasion the loss of data was due to the motion sensor and on the other it was due to the previously mentioned data processor failure.

Ship's Heading Sensor - Humphrey, Inc. - Model DG04-0901-1

The instantaneous ship's heading is measured by a Humphrey, Inc. Gyrocompass, Model DG04-0901-1. The gyrocompass is mounted on a rotatable base so that the Humphrey gyro heading can be adjusted to match the ship's heading.

As in the Humphrey motion sensor, angular displacements are measured proportionally to the output of a potentiometer. The heading output is continuous from 0-360° except for a 1-2° non-shortening gap in the potentiometer. This gap, however, had no effect on the results as it does not occur at a heading of interest.

The Scorsby of the gyrocompass is not more than 10°/hour. (Scorsby is defined as alternate clockwise and counterclockwise $\pm 7.5^\circ$ roll, pitch and yaw movements at 6.0 cycles per minute). The drift rate of the gyrocompass was minimized by adjusting it to the latitude at the Columbia River. The drift was observed to be approximately 5°/hour.

The heading sensor utilizes the same 28 VDC power supply as the motion sensor. However, because there is no internal inverter in the heading sensor, a Humphrey Power Supply-Inverter, Model No. P306-0201-1 was needed to convert the voltage to 115 VAC, 400 Hz, single phase. The heading sensor is also very compact with an overall height of 8.15" and a diameter of 3.13". The mounting base is 5" x 5". Total weight is 3.5 lbs.

3.0 FIELD OPERATIONS

3.1 DATA COLLECTION PERIODS

Vessel motion measurements at the Columbia River entrance were carried out during three periods, from May through June of 1978, from November 1978 through March 1979, and from October 1979 through April 1980. The initial field period, which incorporated seven bar crossings, was intended to pick up the last potentially rough weather of the spring season while providing a shakedown period for the instrument package.

Field operations were discontinued during the calm summer months and were resumed at the onset of the winter season. Phase I winter data collection began in November 1978 and lasted approximately five months. During this period twenty-two crossings were accomplished before discontinuation in March 1979. Thus altogether twenty-nine transits were conducted during the Phase I study.

Field operations for the Phase II winter data collection began in mid-October 1979 and were completed in early-April, 1980. During this period a total of twenty-four bar crossings was carried out as a continuation of the twenty-nine done in Phase I. As in the Phase I study, operations were timed to coincide with the season believed to be the most critical from the standpoint of vessel motions and channel requirements. With the onset of the calmer summer season field data collection operations were concluded.

3.2 MOBILIZATION

Mobilization for each of the two field periods consisted of three major tasks: establishing contacts and arranging for passage with ship owners, installing the two Mini Ranger shore stations at the river mouth, and establishing a field office from which to conduct operations.

Prior to commencement of field operations in May 1978 arrangements were made with Chevron Shipping Company and Weyerhaeuser Company to instrument their vessels transiting the Columbia River mouth. These vessels were selected not only because they were representative of the deeper draft ships utilizing the entrance channel, but also because they permitted embarkation and disembarkation at convenient West Coast ports. The cooperation and assistance of the ship owners and operators in facilitating shipboard operations were also a major consideration.

During the Phase I winter period of field measurements, passage was obtained on vessels belonging to Matson Navigation Company and a consortium of Japanese lines in addition to Chevron. Weyerhaeuser vessels were unavailable at this time. The Phase II winter period was conducted initially with passage available on all four groups of ships mentioned above and eventually an addition of one more shipping line, Act Maritime, which operates auto carriers between the West Coast of North America and Japan. After a two-month period, however, Chevron ships became unavailable to the project due to a labor dispute and the operation was forced to concentrate on the remaining lines.

Prior to the beginning of shipboard measurements in each of the field periods, two Mini Ranger transponders were installed at the river mouth to provide references for the positioning system. The shore stations were mounted on the Cape Disappointment watch tower ($46^{\circ} 16' 33.33''$ N, $124^{\circ} 3' 3.76''$ W) and on a U.S. Coast Guard direction finder calibration pole near the Hammond Mooring Basin ($46^{\circ} 12' 24.54''$ N, $123^{\circ} 57' 16.28''$ W) (Reference Fig. 1). These stations were selected to give both an unobstructed view of the channel, a requirement of the microwave positioning system, and the optimum "angle of cut" between stations to maximize positional accuracy. The resulting accuracy as dictated by the range accuracy of the Mini Ranger system and the geometry of the shore station - entrance channel configuration was estimated to be approximately ± 35 ft

in the vicinity of buoy No. 2 and \pm 65 ft in the vicinity of buoy No. 12.

The position of each shore station in terms of the state plane coordinate system was established by the U.S. Army Engineer District, Portland, at the outset of the project to provide a known reference for all shipboard position data. For the Cape Disappointment station the coordinates are 971,053' N and 1,102,208' E, and for the Hammond station they are 944,817' N and 1,125,518' E. The distance between the two stations was computed and utilized to calibrate the system on site by bringing the receiver-transmitter and console to each station and reading the distance to the other. This procedure was employed at the beginning of each field period and periodically throughout the season to verify calibration. In all checks ranges were within the \pm 10 ft accuracy of the Mini Ranger system.

A field office was established in the San Francisco Bay area for both phases of the field operations. This area was selected as a base of operations because vessels from all shipping companies except the Japanese Six lines called there enroute to or from the Columbia River. The unpredictable schedule followed by the Chevron, Matson and Act Maritime ships departing the San Francisco Bay made this area particularly suitable for a field office.

3.3 SHIPBOARD OPERATING PROCEDURES

Tetra Tech personnel boarded ships with the SMPS at the dock before the ship sailed enroute to or from the Columbia River. Personnel and equipment stayed on board until the ship docked at the next port. Ports of call for the ships involved in the Phase I study included San Francisco Bay, California; Portland and Coos Bay, Oregon; Seattle, Longview, Everett and P. Wells, Washington; and Vancouver, British Columbia. As originally conceived, the personnel with the SMPS would embark

and disembark at the same time as the Columbia River Bar Pilot. This idea proved to be impractical, however, due to both the difficulty in boarding at sea with 400 pounds of equipment, and the time required to ready the SMPS.

Transit times from the ports of departure to the mouth of the Columbia River varied, with approximately eight hours required from Portland, sixteen hours from Vancouver, British Columbia and forty hours from San Francisco. This time was used for filling out data sheets and setting up the SMPS. Data sheets from Voyage No. 9 are presented in Appendix C to show what information was recorded. For each voyage the ship CG had to be calculated from the current loading conditions which were made available to us by the ship's officers.

Shipboard operating procedures for Phase II were consistent with Phase I procedures. The inclusion of Act Maritime vessels in Phase II introduced only one additional port of call, Long Beach, California. Transit time from Long Beach to the mouth of the Columbia River was approximately 60 hours. Also, several additional data items were recorded for each bar crossing. The additional data included the observed pitch and roll period of the ship while transiting the entrance channel, observed currents at buoys No. 2 and No. 12, and a record of the pilot's commands and the event responsible for the command.

The SMPS was set up in the wheelhouse of the ship at least eight hours prior to reaching the mouth of the river. Whenever possible the SMPS was located on the navigational chart table as this area usually provided the best working area. All of the instrumentation was secured to the working surface to keep it in place when the ship pitched and rolled.

Special care was taken to locate the motion sensor and positioning system receiver-transmitter as near the ship's center line as possible. Ideally the motion sensor would be located at the CG to avoid acceleration effects caused by pitch and roll.

The receiver-transmitter had to be mounted outside the wheelhouse so there would be no obstructions between the shore reference stations and the receiver-transmitter, and secondly, mounted on the center line if possible so the most representative track of the ship could be obtained. Because the receiver-transmitter was mounted above the wheelhouse on the compass bridge deck a 100 ft interconnecting cable was needed. The cable had to be passed through one of the doors or portholes, if possible on the leeward side of the ship. The exact location of the receiver-transmitter was also measured and recorded.

Once the system was set up a preliminary check was made to verify that all of the instrumentation was in working order. Preparations for the actual bar crossing began 1 to 2 hours in advance of picking up the pilot. By this time the draft of the ship was recorded and regarded as that for the bar crossing. The SMPS was powered up and the time of day clock set in accordance with the ship's chronometer to local time and the pre-run equipment test performed. Items checked in both the pre-run and post-run equipment check are shown on pages 5-7 of Voyage No. 9 data sheets as shown in Appendix C. The pre-run check involved cleaning the tape heads, observing that the motion sensor accurately measured a known angle (-45° , 0° , $+45^\circ$) for both pitch and roll and responded to accelerations, setting the ship heading sensor to match the ship's heading, and exercising the circuitry of the positioning system console. After performing the above operations, data were recorded for a period of approximately 1 minute to check the tape recorder. Results of the motion sensor and tape recorder tests were printed on the Hewlett Packard strip printer and included in the data sheets.

Pre-run weather observations were made upon arrival at the pilot station. These observations included a general description of the weather, air temperature, visibility, wind speed and direction, and sea and swell heights, periods, and

directions. Because observations were made from the bridge wing of the ship, it was difficult to estimate small seas. For this reason the pilot was often consulted, not only for sea conditions but also visibility.

The actual data recording began in the vicinity of buoy No. 2 inbound or buoy No. 11 outbound. Just prior to commencing, the ship heading sensor was again set to match the corrected ship's gyro. Once the actual recording began, one person would monitor the equipment while the other recorded the pilot's commands and comments. At periodic intervals the ship's speed and RPM (or propeller pitch in the case of variable pitch propellers) were recorded. Also, simultaneous readings of the ship heading sensor and the ship's gyro were recorded to check the deviation of the heading sensor.

The person with the pilot recorded his comments concerning the currents, sea state, other vessel traffic and anything else that may have affected his course of action. An attempt was also made to record the commands to the Quartermaster or the Officer on watch concerning course and speed. During the initial period of the field operations (May-June 1978) the pilot's comments were written on paper, but this proved to be too time consuming and a dictaphone was utilized throughout subsequent periods of the field operation. The pilots were very cooperative in explaining their actions and perceptions.

Data recording was stopped around buoy No. 11 when inbound and buoy No. 2 when outbound. As soon as recording stopped a final deviation check was made on the heading sensor. The pilot was then asked to rate the voyage as "easy", "moderate", or "difficult". These ratings were based primarily on the wave conditions, but other factors were necessarily considered as well: ship draft, ship response, visibility, other traffic, tidal and other currents, stage of the tide. In addition, the pilot was asked to sketch his intended course as shown on page 2 of the data sheets in Appendix C.

At this time a post-run weather observation and equipment check was performed. These are the same as the pre-run observation and check discussed earlier. In addition a data editing program was run to verify that the data was recorded with no gaps. Finally, when available, a copy of the ship's echo sounder record and course and rudder angle record for the time corresponding to the bar crossing was obtained.

It should be noted that during the initial period of field operations (May-June 1978) a flux-gate compass was used for the ship heading sensor. Because of the influence of the ship's steel superstructure, it was necessary to mount the sensor aloft on an aluminum pole to minimize the ship's magnetic influence. Even with this arrangement the deviation rate was found to be variable and unpredictable, causing the ship heading data from the first phase of field operations to be unusable. The problem was solved by replacing the flux-gate compass with a gyrocompass for subsequent operations. The gyrocompass proved to work very well.

With the data acquisition completed the SMPS was removed from the wheelhouse and made ready for disembarkation at the next port.

3.4 FIELD OFFICE OPERATIONS

The field office was used as a base for scheduling voyages, transferring data, and instrumentation maintenance and calibration. Upon return to the field office the data was transferred from magnetic tape to flexible disk. The disks, along with other pertinent data, were then mailed to the home office for data reduction and analysis.

Periodic instrument calibration checks were performed at the field office in addition to any necessary maintenance such as repairing cables or wiring. The calibration checks were performed approximately once a month. The motion sensor was

checked by placing it on a near level surface and rotating it 360° in 90° increments. At each of the four positions the pitch and roll readings were recorded. The readings from positions 1 and 3 and 2 and 4 were then averaged to see if they fell within the accuracy of the instrument. Also, the pitch and roll measurements at alternate positions were compared to see if the angles measured were the same.

The gyrocompass was checked for accuracy and drift. The compass was rotated through 360° at 45° increments and the corresponding readings compared for accuracy. Drift rate was checked by setting the gyro to a known heading and running it for approximately 45 minutes. At the end of 45 minutes the heading was recorded and the drift rate computed from the change in heading.

The entire system was then checked by simulating a voyage. Data were recorded for approximately one-half hour and then edited for any data gaps.

4.0 BASIC DATA

4.1 VOYAGE DESCRIPTIONS

There were altogether 53 measurements conducted, 29 for Phase I and 24 for Phase II, and a total of 18 ships involved in the field study spanning the period from May 1978 to April 1980. The basic data for these voyages and the environmental conditions at each transit are summarized in Tables 1a and 1b. Table 1a covers the voyages for Phase I and Table 1b for Phase II. These tables are intended to briefly describe only the background information of each transit; other details can be found from other tables by cross referencing the voyage numbers.

4.2 VESSEL CHARACTERISTICS

The current thinking on the vessel size appropriate for the Columbia River entrance channel design is 600 ft length, 85 ft beam, and 34 ft draft with a deadweight tonnage of 30 to 35 thousand tons*, although larger vessels up to 43 ft draft have been utilizing the entrance with the aid of tides and river stages. Consequently, a draft of 34 ft has been regarded as a norm in the vessel selection for the present study.

A summary of the vessels utilized to conduct the motion study is presented in Table 2. The vessels fall into four main categories: oil carriers, container carriers, bulk carriers, and auto carriers. In a general sense, these ships were selected as representative of the deeper draft vessels which frequent the entrance channel. The choice of specific ships, however, depended upon the willingness of the owners to participate in the study and the availability of the ships for berthing.

There were altogether 18 ships selected in the present measurement program. A total of 17 transits was made on six oil

* Information from U.S. Army Engineer District, Portland, 1977.

TABLE 1a
SUMMARY OF VOYAGE DESCRIPTIONS
(PHASE I)

VOYAGE NO.	DATE	VESSEL		TRANSIT DIRECTION	CONDITIONS IN VICINITY OF LIGHTSHIP *										PILOT'S RATING OF TRANSIT
					WEATHER	VISIBILITY (NM)	WIND		SEA	SWELL		PERIOD (SEC)	TIDAL CURRENT		
		NAME	TYPE				DIRECTION (KTS)	SPEED		DIRECTION	HT (FT)				
1	5/26/78	CHEVRON LOUISIANA	OIL CARRIER	IN	BROKEN CLOUDS	10	NW	15-20	NW, 2-4 FT	NW	6-8	8	FLOOD	EASY	
2	5/29/78	CHEVRON ARIZONA	OIL CARRIER	IN	FAIR w/ SCATTERED CLOUDS	UL	NW	10-15	NW, 2-3 FT	W	6	8	SLACK	EASY	
3	6/05/78	HOECH MALLARD	BULK CARRIER	IN	FAIR w/HAZE	6-8	WNW	5	SLIGHT CHOP	W	4	8-10	SLACK	EASY	
4	6/07/78	HOECH MALLARD	BULK CARRIER	OUT	FAIR w/HIGH CLOUDS	UL	W	5-8	SLIGHT CHOP	WSW	1-3	8-10	EBB	EASY	
5	6/21/78	CHEVRON OREGON	OIL CARRIER	IN	OVERCAST w/ SHOWERS	3-4	NW	5	SLIGHT CHOP	WNW	8-10	8	FLOOD	EASY	
6	6/23/78	HOECH MARLIN	BULK CARRIER	IN	BROKEN HIGH CLOUDS	UL	WNW	<5	CALM	NW	4-6	8	SLACK	EASY	
7	6/24/78	HOECH MARLIN	BULK CARRIER	OUT	FAIR w/ SCATTERED CLOUDS	UL	W	5-8	SLIGHT CHOP	WNW	2-4	6-8	SLACK	EASY	
8	11/01/78	CHEVRON WASHINGTON	OIL CARRIER	IN	FAIR w/SLIGHT HAZE	UL	NE	<5	CALM	NW	10	10-12	EBB	MODERATE	
9	11/04/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	FAIR	UL	NW	15	NW, 2-4 FT	WNW	10-12	10	SLACK	EASY	
10	11/09/78	CHEVRON WASHINGTON	OIL CARRIER	IN	FAIR w/ SCATTERED CLOUDS	UL	NW	15	NW, 2-4 FT	NW	6	8	FLOOD	EASY	
11	11/10/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	FAIR	UL	NE	10-15	NE, 1-2 FT	NW	5	8	EBB	EASY	
12	11/28/78	ALASKA MARU	CONTAINER CARRIER	IN	OVERCAST w/ SHOWERS	5-10	SSE	5-8	SLIGHT CHOP	WSW	6	8	EBB	EASY	
13	12/03/78	CHEVRON COLORADO	OIL CARRIER	IN	OVERCAST	UL	SE	10-15	SE, 3 FT	W	(SLIGHT)	*	EBB	EASY	
14	12/04/78	CHEVRON COLORADO	OIL CARRIER	OUT	SCATTERED LOW CLOUDS	UL	NW	25-30	NW, 4-6 FT	WNW	8-10	8-10	SLACK	MODERATE	
15	12/15/78	HILLIER BROWN	OIL CARRIER	IN	MOSTLY CLEAR w/ SCATTERED SQUALLS	UL	W	10-15	W, 2 FT	W	15-20	8	EBB	DIFFICULT	
16	12/17/78	HILLIER BROWN	OIL CARRIER	OUT	OVERCAST w/ SCATTERED SQUALLS	UL EXCEPT IN SQUALLS	SSE	10-12	SSE, 2-3	W	12-18	8	SLACK	DIFFICULT	
17	12/29-30/78	ALASKA MARU	CONTAINER CARRIER	IN	OVERCAST	UL	SE	10	SLIGHT CHOP	*	(SLIGHT)	*	FLOOD	EASY	
18	1/16/79	MAUNA LEI	CONTAINER CARRIER	IN	OVERCAST	UL	WSW	5	SLIGHT CHOP	WNW	4-6	8	EBB	EASY	
19	1/19/79	MAUNA LEI	CONTAINER CARRIER	OUT	OVERCAST w/ DRIZZLE	2	ESE	5-8	SLIGHT CHOP	W	15-18	10-11	EBB	MODERATE	
20	1/21/79	HIKAWA MARU	CONTAINER CARRIER	IN	OVERCAST w/ DRIZZLE	3-4	NW	<10	SLIGHT CHOP	WSW	10-12	10-11	SLACK	MODERATE	
21	1/24/79	GOLDEN ARROW	CONTAINER CARRIER	IN	OVERCAST w/ SNOW SHOWERS	VARIABLE BUT >4	ENE	5	SLIGHT CHOP	WNW	10	8-10	FLOOD	MODERATE	
22	1/28/79	ALASKA MARU	CONTAINER CARRIER	IN	FAIR	UL	NE	8	SLIGHT CHOP	WNW	10-12	10	EBB	EASY	
23	2/07/79	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	OVERCAST w/ SHOWERS	5-7	E	5-10	SLIGHT CHOP	W	10	10	SLACK	MODERATE	
24	2/11/79	BEISHU MARU	CONTAINER CARRIER	IN	MODERATE FOG w/ RAIN	3/4	S	10	SLIGHT CHOP	SSW	5	8	SLACK	EASY	
25	2/22/79	GOLDEN ARROW	CONTAINER CARRIER	IN	BROKEN CLOUDS w/ SCATTERED SHOWERS	UL	ESE	8-10	ESE, 1-2 FT	SSW	3-4	8	SLACK	EASY	
26	2/27/79	ALASKA MARU	CONTAINER CARRIER	IN	PARTLY CLOUDY	UL	WSW	6-8	SLIGHT CHOP	SW	6-8	3	FLOOD	EASY	
27	3/14/79	BEISHU MARU	CONTAINER CARRIER	IN	OVERCAST w/ LIGHT RAIN	8	S	5	SLIGHT CHOP	W	4-6	10	FLOOD	EASY	
28	3/22/79	CHEVRON WASHINGTON	OIL CARRIER	IN	FAIR	UL	W	5	CALM	WNW	5	10	FLOOD	EASY	
29	3/23/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	DENSE PATCHY FOG	200 YDS.	CALM		CALM	W	4-6	10	SLACK	EASY	

* THE LIGHTSHIP COLUMBIA WAS REMOVED FROM SERVICE IN NOVEMBER 1979 AND REPLACED BY A NAVIGATIONAL LIGHTBUOY
* ACCURATE OBSERVATION PRECLUDED BY DARKNESS

EXPLANATORY NOTES FOR ENVIRONMENTAL CONDITION SUMMARY TABLE

WIND	BY OBSERVATION	TIDAL CURRENT	FROM NOAA TIDAL CURRENT PREDICTIONS FOR 1/4 MILE SSE OF CAPE DISAPPOINTMENT LIGHTHOUSE IN THE VICINITY OF BUOY NO. 12). IF THE ENTIRE DATA ACQUISITION PERIOD FOR A PARTICULAR TRANSIT OCCURRED WITHIN ONE HOUR OF PREDICTED SLACK WATER, THE TIDAL CURRENT IS DENOTED AS "SLACK". IF ANY PORTION OF THE DATA ACQUISITION PERIOD WAS MORE THAN ONE HOUR AWAY FROM THE PREDICTED SLACK WATER, THE TIDAL CURRENT APPEARS AS "FLOOD" OR "EBB" AS APPROPRIATE.
SEA	BY OBSERVATION AND CONSULTATION WITH PILOT. HEIGHT IS GIVEN ONLY WHEN IT APPEARED TO EXCEED 1 FOOT. SEA HEIGHTS LESS THAN 1 FOOT ARE DENOTED AS "SLIGHT CHOP".	PILOT'S RATING OF TRANSIT	ASKED OF THE PILOT UPON COMPLETION OF THE TRANSIT. WAVE CONDITIONS WERE THE PRIMARY DETERMINANT, BUT OTHER FACTORS WERE NECESSARILY CONSIDERED AS WELL: SHIP DRAFT, SHIP RESPONSE, VISIBILITY, OTHER TRAFFIC, TIDAL AND OTHER CURRENTS, STAGE OF THE TIDE. A SEA CONDITION PRODUCING AN "EASY" TRANSIT IN FAIR WEATHER WITH NO OPPOSING TRAFFIC COULD RESULT IN A "MODERATE" CROSSING IF POOR VISIBILITY AND OPPOSING TRAFFIC WERE ENCOUNTERED.
SWELL	BY OBSERVATION AND CONSULTATION WITH PILOT. IT SHOULD BE NOTED THAT SWELL HEIGHTS LESS THAN 10 FEET ARE DIFFICULT TO ESTIMATE ACCURATELY FROM SHIPBOARD.		

TABLE 1b
SUMMARY OF VOYAGE DESCRIPTIONS
(PHASE II)

VESSEL					CONDITIONS IN VICINITY OF LIGHTSHIP*									
VOYAGE NO.	DATE	NAME	TYPE	TRANSIT DIRECTION	WEATHER	VISIBILITY (NM)	WIND		SEA		SWELL		TIDAL CURRENT	PILOT'S RATING OF TRANSIT
							DIRECTION	SPEED (KTS)	DIRECTION	HT (FT)	PERIOD (SEC)			
30	10/16/79	CHEVRON ARIZONA	OIL CARRIER	IN	OVERCAST	UL	S	10-15	1-2 FT	NW	5	8	FLOOD	EASY
31	10/17/79	CHEVRON ARIZONA	OIL CARRIER	OUT	HIGH OVERCAST	UL	NW	5-8	SLIGHT CHOP	W	3-10	8	EBB	EASY
32	10/28/79	ALASKA MARU	CONTAINER CARRIER	IN	CLEAR	UL	S	5	SLIGHT CHOP	W	6-8	10	FLOOD	EASY
33	11/14/79	HOEGH MUSKETEER	BULK CARRIER	IN	CLEAR	UL	E	15	1-2 FT	W	2-4	10	FLOOD	EASY
34	11/17/79	HOEGH MUSKETEER	BULK CARRIER	OUT	OVERCAST W/ RAIN	UL	W	10-12	1-2 FT	W	6	9	FLOOD	EASY
35	11/21/79	MAUNA LEI	CONTAINER CARRIER	OUT	CLEAR	UL	ENE	10-15	1-2 FT	SW	6-8	8-10	EBB	EASY
36	11/26/79	GOLDEN ARROW	CONTAINER CARRIER	IN	CLEAR	UL	ENE	5-8	SLIGHT CHOP	W	3-6	8	EBB	EASY
37	11/28/79	HOEGH MASCOT	BULK CARRIER	IN	BROKEN	UL	ESE	30-35	4 FT	W	6-8	10	EBB	EASY
38	12/03/79	HOEGH MASCOT	BULK CARRIER	OUT	HEAVY OVERCAST W/ RAIN	1/2 to 3/4	S	40+	S. 5-10 FT	SLIGHT OBSCURED BY SEAS			EBB	MODERATE
39	12/16/79	CHEVRON WASHINGTON	OIL CARRIER	IN	HIGH OVERCAST	UL	E	15	2-3 FT	W	4-6	8	FLOOD	EASY
40	12/18/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	HEAVY OVERCAST W/ LIGHT RAIN	5	SSE	12	4 FT	SW	6	8	FLOOD	EASY
41	1/20/80	HIKAWA MARU	CONTAINER CARRIER	IN	CLEAR	UL	E	5	SLIGHT CHOP	SSW	3-5	8-10	FLOOD	EASY
42	1/24/80	GOLDEN ARROW	CONTAINER CARRIER	IN	OVERCAST W/ LIGHT MIST	7	E	5	SLIGHT CHOP	WNW	6-8	13	EBB	EASY
43	2/04/80	WORLD WING	AUTO CARRIER	IN	CLEAR W/ SOME OVERCAST	UL	E	8-10	SLIGHT CHOP	W	6-8	10	FLOOD	EASY
44	2/06/80	WORLD WING	AUTO CARRIER	OUT	OVERCAST	3-5	WSW	25-30+	6-7 FT	W	10-15	8	FLOOD	MODERATE
45	2/10/80	HOEGH MUSKETEER	BULK CARRIER	IN	SCATTERED OVERCAST	UL	E	15-20	2-3 FT	W	4-5	10	FLOOD	EASY
46	2/14/80	HOEGH MUSKETEER	BULK CARRIER	OUT	SLIGHT OVERCAST	UL	E	10-15	2-4 FT	SW	4-6	8-10	EBB	EASY
47	3/04/80	MAUNA LEI	CONTAINER CARRIER	IN	OVERCAST	UL	E	5-10	1-2 FT	WNW	6-8	9-10	EBB	EASY
48	3/10/80	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	LIGHT RAIN	UL	W	5	SLIGHT CHOP	W	2-4	9-9	EBB	EASY
49	3/18/80	HOEGH MERCHANT	BULK CARRIER	IN	OVERCAST	15-20	E	5-10	2-3 FT	W	4-6	13	FLOOD	EASY
50	3/22/80	HOEGH MERCHANT	BULK CARRIER	OUT	LOW OVERCAST W/ LIGHT RAIN	3-5	SW	10-15	1-2 FT	WNW	9-10	12-13	FLOOD	MODERATE
51	3/26/80	GOLDEN ARROW	CONTAINER CARRIER	IN	OVERCAST	20	NNW	15-20	2-4 FT	WNW	6-8	6-8	EBB	EASY
52	4/01/80	ALASKA MARU	CONTAINER CARRIER	IN	CLEAR	UL	E	5-7	1-2 FT	WNW	8-10	12	EBB	MODERATE
53	4/03/80	HOEGH MALLARD	BULK CARRIER	IN	OVERCAST	3-5	E	5-10	SLIGHT CHOP	W	2-4	9-10	FLOOD	EASY

*THE LIGHTSHIP COLUMBIA WAS REMOVED FROM SERVICE IN NOVEMBER 1979 AND REPLACED BY A NAVIGATIONAL LIGHTBOAT

REFER TO TABLE 1a FOR EXPLANATORY NOTES FOR ENVIRONMENTAL CONDITION SUMMARY TABLE

TABLE 2 VESSEL SUMMARY

Vessel Type	No. of Transits	Principal Dimensions and Main Characteristics						
		Length Overall LOA	Length Between Perpendiculars LBP	Breadth (Molded) (FT)	Depth (Molded) (FT)	Design Draft (FT)	Displacement (LT)	Dead-Weight Tonnage DWT
I. Oil Carriers	A) Chevron Gas Turbine Class	651'-4"	625'-0"	96'-0"	50'-0"	34'-0"	44500	35000
								11300 SHP
								15
	B) "Billyet Brown"	523'-6"	501'-0"	68'-0"	40'-3"	32'-7" 8	23400	18000
								7000 SHP
								16
II. Container Carriers	A) Japanese Consortium	685'-8"	639'-9"	98'-5"	54'-10"	34'-5"	35500	23000
		697'-2"	656'-2"	98'-5"	53'-6"	34'-6"	36500	24000
		616'-10"	574'-2"	82'-8"	50'-2"	35'-2"	28300	19000
		700'-3"	656'-0"	101'-8"	54'-2"	34'-5"	36700	23000
		718'-6"	669'-4"	102'-5"	62'-0"	36'-10"	45300	27000
	B) Matsen Container/Auto/Single Carrier	630'-4"	606'-0"	71'-6"	52'-0"	32'-10" 4	29300	18000
								9000 SHP
								16
III. Bulk Carriers	A) Hoegh "M" Class	659'-5"	629'-11"	101'-0"	51'-6"	33'-0"	49600	36100
								15000 BHP
								15.3
IV. Auto Carriers	A) Act Maritime	506'-8"	557'-8"	90'-7"		29'-0"	20500	23000
								N/A
								21.0

carriers operated by Chevron Shipping Company. Of these six ships, five belonging to the Chevron Gas Turbine class have identical lines with a deadweight capacity of 35,000 tons. The gas turbine tankers are characterized by fairly broad lines typical of a modern oil carrier, with all living quarters and the bridge in a single superstructure aft. Propulsion is turbo-electric with a single variable-pitch propeller. During their several years of operation, they have developed a reputation as being difficult to steer.

The remaining Chevron ship, the *Hillyer Brown*, is basically a T-2 class tanker. As such, it is considerably smaller (17,000 DWT) than the Gas Turbine class with somewhat finer lines. The *Brown* is powered by a conventional steam plant with the wheelhouse located forward. All six Chevron tankers travel primarily between Alaska, Hawaii, and ports on the U.S. West Coast.

Seventeen of the 21 transits aboard container vessels were conducted on ships belonging to a Japanese consortium. The consortium carries containerized cargo between Japan and the West Coast ports of Seattle, Vancouver, B.C., and Portland. Although each of the five Japanese vessels is unique, they all possess relatively fine lines, a sea speed in excess of 20 knots, and excellent sea-keeping characteristics. All five ships contain a single superstructure aft and utilize diesel propulsion.

The only American container vessel monitored in the course of the study, Matson Navigation Company's *Mauna Lei*, represents an older, slower category of ships. The hull is a modified C-4 transport with steam propulsion. In addition to containers, the *Mauna Lei* carries automobiles and molasses between West Coast ports and Hawaii.

Thirteen transits were conducted on modern 35,000 DWT bulk carriers of the Höegh "M" class. Under longterm charter to the Weyerhaeuser Company, the Norwegian-owned Höegh ships transport forest products (including plywood, lumber and pulp) from West Coast ports to Europe. In addition, they carry containers, often as deck cargo. The Höegh ships, utilizing diesel propulsion, possess relatively fine lines but large freeboard with a single superstructure aft. Particularly when carrying a deck cargo of containers, they are noted for rolling heavily.

One additional type of ship was utilized for the Phase II operations of the study. This was the *World Wing*, an automobile carrier, owned by Act Maritime of Japan and operating on an unscheduled basis between Japan and several North American West Coast ports. With a large amount of sail area and relatively shallow draft, the *World Wing* is noted for heavy rolling and difficult steerage in cross winds.

Whereas the general information on all the 18 ships has been given in Table 2, their transit and loading conditions on each voyage are summarized in Tables 3-a and 3-b. The actual draft, displacement and the location of the ship CG at each transit are also included in this table. For some transits the corresponding stability criterion, GM_{τ} (transverse metacentric height) and GM_{λ} (longitudinal metacentric height), were computed with available information provided by the ship's engineering officers and are summarized in Appendix D.

TABLE 3a
SUMMARY OF VESSEL CONDITION AT TRANSIT
(PHASE I)

VOYAGE NO.	DATE	VESSEL		TRANSIT DIRECTION	VESSEL SPEED (KTS.)	PRINCIPAL DIMENSIONS					LOADING CONDITIONS					
		NAME	TYPE			LOA (FT)	LBP (FT)	BREADTH (FT)	DESIGN DRAFT (FT)	DWT (LT)	FWD DRAFT (FT)	AFT DRAFT (FT)	MEAN DRAFT (FT)	DISPLACEMENT (LT)	LCG (FT)	VCG (FT)
1	5/20/78	CHEVRON LOUISIANA	OIL CARRIER	IN	9-11	651.3	625.0	96.0	34.0	35,000	32.5	33.5	33.0	43,022	322.9	25.4
2	5/29/78	CHEVRON ARIZONA	OIL CARRIER	IN	11-14	651.3	625.0	96.0	34.0	35,000	33.4	33.9	33.7	44,100	319.6	29.4
3	6/05/78	HØEGH MALLARD	BULK CARRIER	IN	12-14	657.8	623.4	101.1	33.0	36,000	21.4	27.6	24.5	35,544	311.8	27.5
4	6/07/78	HØEGH MALLARD	BULK CARRIER	OUT	14	657.8	623.4	101.1	33.0	36,000	23.2	27.8	25.5	37,071	319.3	27.9
5	6/21/78	CHEVRON OREGON	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	34.5	35.5	35.0	46,120	319.5	27.3
6	6/23/78	HØEGH MARLIN	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	26.3	28.8	27.6	40,394	325.2	28.7
7	6/24/78	HØEGH MARLIN	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	27.8	28.3	28.0	41,125	329.1	30.6
8	11/01/78	CHEVRON WASHINGTON	OIL CARRIER	IN	9-13	651.3	625.0	96.0	34.0	35,000	32.8	34.2	33.5	43,840	318.8	29.2
9	11/04/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	12-15	651.3	625.0	96.0	34.0	35,000	27.0	30.0	28.5	36,385	318.9	22.6
10	11/09/78	CHEVRON WASHINGTON	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	33.2	34.7	33.9	44,519	318.4	29.2
11	11/10/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	14-16	651.3	625.0	96.0	34.0	35,000	22.5	24.5	23.5	29,256	325.5	23.4
12	11/28/78	ALASKA MARU	CONTAINER CARRIER	IN	10-19	685.7	639.8	98.4	34.4	23,000	26.5	30.9	28.7	28,288	302.4	35.5
13	12/03/78	CHEVRON COLORADO	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	33.4	34.1	33.8	44,240	319.3	29.1
14	12/04/78	CHEVRON COLORADO	OIL CARRIER	OUT	10-13	651.3	625.0	96.0	34.0	35,000	24.3	19.3	21.8	26,733	317.7	23.2
15	12/15/78	HILLER BROWN	OIL CARRIER	IN	8	523.5	503.0	68.0	32.1	18,000	24.4	29.3	26.8	19,205	248.7	20.9
16	12/17/78	HILLER BROWN	OIL CARRIER	OUT	6	523.5	503.0	68.0	32.1	18,000	25.1	28.2	26.6	19,028	252.9	22.2
17	12/29-30/78	ALASKA MARU	CONTAINER CARRIER	IN	17	685.7	639.8	98.4	34.4	23,000	28.3	29.1	28.8	27,778	307.5	35.9
18	1/16/79	MAUNA LEI	CONTAINER CARRIER	IN	13	630.3	606.0	71.5	32.9	18,000	21.8	30.0	25.9	22,296	299.3	23.2
19	1/19/79	MAUNA LEI	CONTAINER CARRIER	OUT	8	630.3	606.0	71.5	32.9	18,000	22.8	31.5	27.2	23,670	295.4	24.1
20	1/21/79	HIKAWA MARU	CONTAINER CARRIER	IN	14	700.3	656.0	101.7	34.4	23,000	26.8	30.9	28.9	28,926	308.8	37.6
21	1/24/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	25.7	33.7	29.7	22,483	268.8	29.0
22	1/28/79	ALASKA MARU	CONTAINER CARRIER	IN	17	685.7	639.8	98.4	34.4	23,000	28.5	30.6	29.6	29,176	302.3	34.6
23	2/07/79	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	16-21	718.5	669.3	102.4	36.8	27,000	32.6	32.6	32.6	35,101	320.0	37.6
24	2/11/79	BEISHU MARU	CONTAINER CARRIER	IN	16	697.2	656.2	98.4	34.5	24,000	28.1	30.5	29.3	29,544	318.3	31.4
25	2/22/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	28.5	34.6	31.6	24,722	266.6	31.0
26	2/27/79	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	34.4	23,000	30.0	30.9	30.4	30,280	306.0	35.9
27	3/14/79	BEISHU MARU	CONTAINER CARRIER	IN	15	697.2	656.2	98.4	34.5	24,000	27.7	32.4	30.1	30,714	316.7	34.5
28	3/22/79	CHEVRON WASHINGTON	OIL CARRIER	IN	13	651.3	625.0	96.0	34.0	35,000	26.3	28.0	27.2	34,430	320.9	23.4
29	3/23/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	7-14	651.3	625.0	96.0	34.0	35,000	23.3	26.9	25.1	31,520	320.0	23.9

TABLE 3b
SUMMARY OF VESSEL CONDITION AT TRANSIT
(PHASE II)

VOYAGE NO.	DATE	VESSEL		TRANSIT DIRECTION	PRINCIPAL DIMENSIONS							LOADING CONDITIONS				
					VESSEL SPEED (KTS.)	LOA (FT)	LBP (FT)	BREADTH (FT)	DESIGN DRAFT (FT)	DWT (LT)	DRAFT			DISPLACEMENT		
		NAME	TYPE								FWD (FT)	AFT (FT)	MEAN (FT)	LT	WT (FT)	CG (FT)
30	10/16/79	CHEVRON ARIZONA	OIL CARRIER	IN	11-14	651.3	625.0	96.0	14.0	35,000	12.8	13.0	13.0	43,100	124.4	14.1
31	10/17/79	CHEVRON ARIZONA	OIL CARRIER	OUT	11-14	651.3	625.0	96.0	14.0	35,000	11.9	13.4	12.7	43,100	124.4	14.1
32	10/28/79	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	14.4	23,000	10.9	11.6	11.3	31,108	129.3	16.1
33	11/14/79	HÖEGH MUSKETEER	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	25.7	29.3	27.5	43,186	124.4	18.8
34	11/17/79	HÖEGH MUSKETEER	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	27.0	31.2	29.2	43,186	124.4	18.8
35	11/21/79	MAUNA LEI	CONTAINER CARRIER	OUT	13	630.3	606.0	71.5	12.9	18,000	19.1	19.1	19.1	22,270	108.7	14.8
36	11/26/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	15.2	19,000	31.2	34.2	32.7	23,960	127.6	10.6
37	11/28/79	HÖEGH MASCOT	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	21.8	25.5	23.7	43,152	118.6	12.5
38	12/03/79	HÖEGH MASCOT	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	25.3	28.2	26.8	43,152	118.6	12.5
39	12/16/79	CHEVRON WASHINGTON	OIL CARRIER	IN	11-14	651.3	625.0	96.0	14.0	35,000	33.4	33.9	33.7	44,100	120.7	19.3
40	12/18/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	11-14	651.3	625.0	96.0	14.0	35,000	11.5	25.5	23.5	43,200	119.7	14.2
41	1/20/80	HIKAWA MARU	CONTAINER CARRIER	IN	14	700.3	656.0	101.7	14.4	23,000	28.3	30.6	29.5	29,049	110.9	16.6
42	1/24/80	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	15.2	19,000	29.5	32.1	30.8	23,960	127.6	10.6
43	2/04/80	WORLD WING	AUTO CARRIER	IN	16-21	566.7	557.7	90.6	29.0	23,000	22.5	24.3	23.4	26,905	196.3	11.6
44	2/06/80	WORLD WING	AUTO CARRIER	OUT	16-21	566.7	557.7	90.6	29.0	23,000	22.3	21.8	22.3	25,686	100.8	11.6
45	2/10/80	HÖEGH MUSKETEER	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	27.3	31.5	29.3	43,685	127.4	17.6
46	2/14/80	HÖEGH MUSKETEER	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	28.2	31.3	29.8	44,351	130.3	11.2
47	3/04/80	MAUNA LEI	CONTAINER CARRIER	IN	13	630.3	606.0	71.5	12.9	18,000	25.5	25.5	25.5	22,270	108.7	14.8
48	3/10/80	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	16-21	718.5	669.3	102.4	36.8	27,000	30.4	32.6	31.5	33,637	118.4	17.9
49	3/18/80	HÖEGH MERCHANT	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	28.5	33.0	30.8	46,094	*	*
50	3/22/80	HÖEGH MERCHANT	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	30.7	33.7	32.2	48,260	122.4	17.0
51	3/26/80	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	15.2	19,000	28.8	32.8	30.8	23,960	129.0	11.7
52	4/01/80	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	14.4	23,000	31.7	33.5	32.6	33,175	135.7	17.2
53	4/03/80	HÖEGH MALLARD	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	35.0	30.0	27.5	40,261	111.7	25.8

5.0 ENVIRONMENT

5.1 ENVIRONMENTAL SETTING

5.1.1 Location

Located on the Pacific Ocean between the states of Oregon and Washington, the mouth of the Columbia River lies 548 nautical miles north of San Francisco and 145 miles south of the Straits of Juan de Fuca. The lightship Columbia, previously positioned 5.3 nautical miles seaward of the entrance on the entrance range line, was removed from service in November 1979 and was replaced with a 12 m diameter navigational lightbuoy at the same position of 46°11.1' N and 124°11.0' W.

As is evident in Figure 1, the entrance is flanked to the north by Cape Disappointment, a rocky headland rising to a height of approximately 280 ft, and Peacock Spit, a sand shoal. To the south, the entrance is bounded by an extensive sand shoal known as Clatsop Spit.

5.1.2 Meteorological Considerations

Winds

Wind conditions at the mouth of the Columbia River exhibit a distinct seasonal variation. During the winter months of September through March, the prevailing winds blow from the southeast quadrant. The winter period is characterized by severe storms and associated strong winds from the south and southwest. Based on a 25-year summary of wind data compiled at Clatsop County Airport through 1978 (U.S. Department of Commerce, 1979), the maximum recorded wind speed for such storms is 55 miles per hour (fastest mile). Storm conditions may persist for several days and are accompanied by extremely heavy seas.

During the summer months, the prevailing winds blow from the northwest through west and generally remain light. Storms are less frequent and of a lesser intensity than those experienced during the winter months.

A wind rose summarizing 11 years of observations at Clatsop County Airport, 1954-1964, is presented in Figure 5.

Visibility

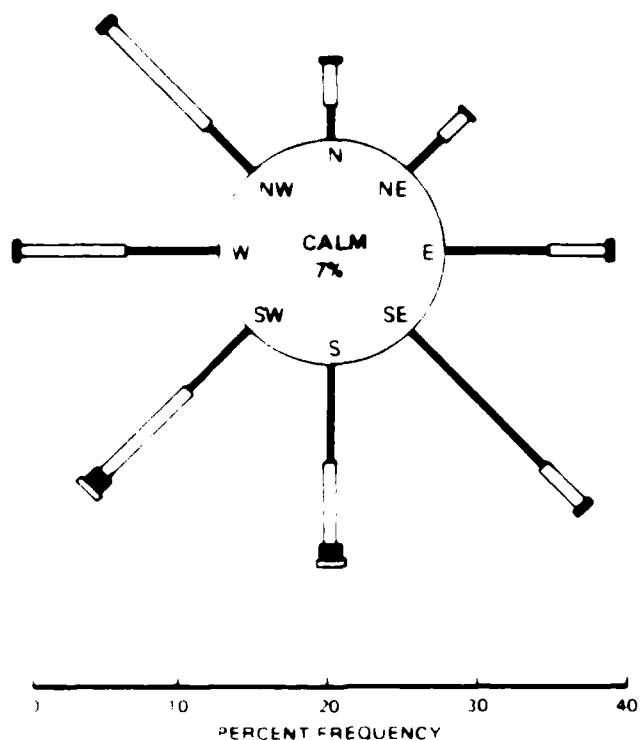
Visibility at the mouth of the Columbia River is subject to impairment by fog, low clouds and heavy rain. Based on a 25 year observation period at Clatsop County Airport, U.S. Department of Commerce, 1979, heavy fog is most prevalent during the months of August, September and October, and least prevalent during the spring and early summer. Visibility was reduced to one-quarter mile or less an average of 41 days per year, with the highest monthly incidence of heavy fog represented by 7 days during October. Primarily in the form of rain, precipitation in excess of 0.01 inch occurred an average of 198 days per year and was most frequent during the winter storm period.

Figure 6 displays the monthly percent frequency of visibility less than two nautical miles based on ship observations at the coast in the general vicinity of the river mouth. As in the case of the Clatsop County Airport data, the higher incidence of impaired visibility from late summer through the winter is clearly evident.





5.1.3 Oceanographical Considerations

Tides

The tides at the Columbia River entrance are of the mixed type with two highs and two lows of unequal height occurring each

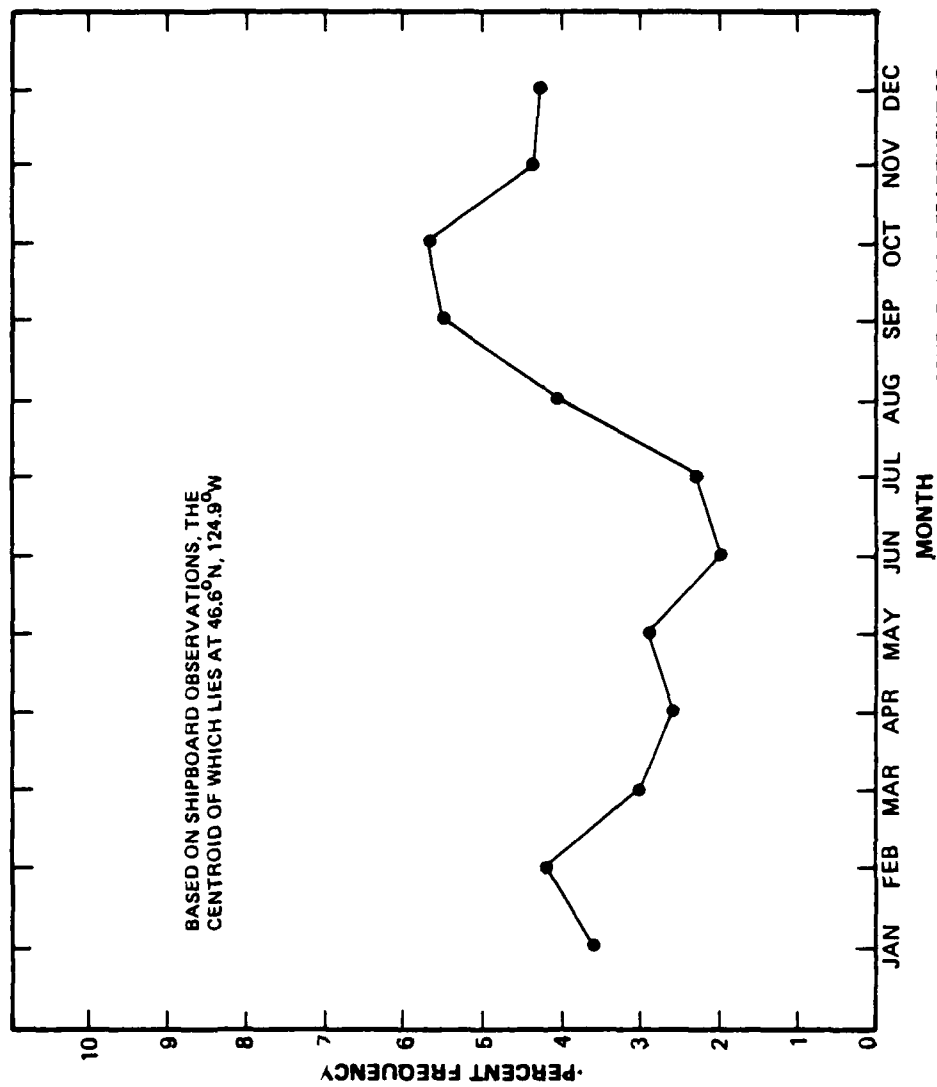


MEAN VELOCITY IN MILES PER HOUR SHOWN BY WIDTH OF LINES:

- 0 TO 7 MILES IS SHOWN THUS 
- 8 TO 18 MILES IS SHOWN THUS 
- 19 TO 31 MILES IS SHOWN THUS 
- 32 TO 46 MILES IS SHOWN THUS 

BASED ON WIND OBSERVATIONS AT CLATSOP
COUNTY AIRPORT FOR THE PERIOD 1954 - 1964

FIGURE 5 - WIND ROSE



SOURCE: U.S. DEPARTMENT OF
COMMERCE, 1976, p. T - 10

FIGURE 6 -- MONTHLY PERCENT FREQUENCY OF VISIBILITY LESS THAN 2 NAUTICAL MILES

lunar day. The various tidal datums at Astoria, Oregon may be summarized as follows:

Record High		12.1 feet
Extreme Predicted High*		10.2
Mean Higher High Water (MHHW)		8.30
Mean High Water (MHW)		7.60
Mean Tide Level (MTL)		4.35
Mean Sea Level (MSL)		4.3
National Geodetic Vertical Datum (NGVD)		3.05
Mean Low Water (MLW)		1.10
Mean Lower Low Water (MLLW)		0.00
Extreme Predicted Low*		-2.1
Record Low		-2.8

Source: Harris [10].

The extreme predicted range of tides is thus 12.3 ft, the mean diurnal range (MHHW to MLLW) 8.30 ft, and the mean range (MHW to MLW) 6.50 ft. The relatively large difference between the mean diurnal range and mean range indicates a sizable inequality in the heights of the two high and two low tides which occur each lunar day. HHW precedes LLW, causing a particularly large ebb relative to the other three tides which occur per day.

Tide heights and times predicted for the river mouth are subject to considerable variation due to the influence of river discharge and wind set-up along the coast.

Currents

Currents experienced at the Columbia River Entrance are produced by three major influences, astronomical tides, river discharge, and wind-induced coastal currents. The most

* Predicted for the period 1963-1981

important of these is the astronomical tide, but tidal currents may be modified both as to velocity and time of slack by the other factors.

According to the Tidal Current Tables published by the National Oceanic and Atmospheric Administration, Department of Commerce (1978), tidal currents for a location 1.4 nautical miles south southeast of Cape Disappointment Light (near Buoy No. 12; Reference Figure 1) set to the west on the ebb with an average maximum speed of 4.3 knots. The flood sets eastward with a lesser average maximum speed of 2.6 knots. Due to the relatively large diurnal inequality in tide heights discussed in the Tides section of this Section 5.1.3, the ebb flow between HHW and LLW is considerably stronger than the other tidal currents produced each lunar day. Based on tidal current predictions for 1978 and 1979, the maximum strength of ebb expected was 7.1 knots, compared with a maximum flood of 4.6 knots.

River discharge varies seasonally with a peak flow period of approximately 30 to 60 days typically occurring between May and July, and a low flood period in the autumn. The maximum discharge of record exceeded 1,200,000 cubic feet per second during June 1894, whereas the extreme regulated low-water flow at the river mouth is estimated to be 80,000 cubic feet per second (exclusive of tidal exchange)*. During the course of the current study, the discharge measured at Vancouver, Washington ranged between approximately 100,000 and 300,000 cubic feet per second (J.C. Huetter, Acting Chief, Engineering Division, Portland District, Corps of Engineers, 25 May 1979, personal communication).

Considering a transect at the river entrance running approximately north-south between the extreme tips of the jetties (Reference Figure 1), and assuming an average depth of 56.8

* Information from U.S. Army Engineer District, Portland, 1977.

feet at MSL based on the hydrography of the Postdredge Survey, Columbia River Mouth on 5 October 1978 (U.S. Army Engineer District, Portland), the following average current speeds are obtained for various river discharge levels:

Average Current Speeds Attributable to River Discharge

	Discharge (Ft ³ /sec)	Average Current Speed (Knots)
Estimated Extreme Low-Water Flow	80,000	0.1
Approximate Minimum Project Flow	100,000	0.1
Approximate Maximum Project Flow	300,000	0.3
Maximum Recorded Discharge	1,200,000	1.2

It is apparent that, as a general rule of thumb, each 100,000 cubic feet per second of discharge produces an average out-bound current of 0.1 knots at the entrance. It should be remembered that this figure represents an average value for an assumed rectangular cross-section. Actual speeds will vary considerably with depth and location. Nevertheless, in light of the flow rates which prevailed during the course of the study period, discharge-induced currents appear to be relatively minor compared with tidal currents.

Due to their dependence on local weather systems, coastal currents are unpredictable and difficult to quantify. According to Captain Martin West of the Bar Pilots (personal communication, June 1979), the effect of wind-induced currents is most evident seaward of the jetty tips (Reference Figure 1). A westerly-setting ebb at buoy No. 8, for example, may become southwesterly at buoy No. 4 under the influence of a strong northwesterly wind.

An indication of the net current regime which prevails at the river entrance is provided by the following summary of average

speeds measured opposite Clatsop Spit at strength of tides during April, May and September 1959:

Average Maximum Measured Current Speeds

	Tide Stage	No. of Tides Measured	Average Maximum Speed (knots)
Low (Sept.)	Ebb	7	2.9
	Flood	7	2.7
Intermediate (April)	Ebb	8	3.0
	Flood	8	2.3
High (May)	Ebb	17	3.3
	Flood	17	2.0

Source: "Current Measurement Program", U.S. Army Engineer District, Portland, September 1960.

Peak speeds recorded during the 1959 measurements were 6.5 knots on the ebb and 3.6 knots on the flood. During a similar study conducted in 1933, a maximum current of 7.3 knots was observed on the ebb tide at one-tenth depth. These figures agree well with the observation of the Coast Pilot (Department of Commerce, June 1976, p. 238) that ebb currents at times exceed 5 knots, whereas flood currents are generally less than 4 knots. It is also reported in the Coast Pilot that the ebb currents on the north side of the bar attains speeds of 6 to 8 knots. Outside the jetties, current speeds diminish.

Inside the jetties, the net current directions tend to be easterly on the flood and westerly on the ebb (Captain Martin West, June 1979, personal communication). Due to the alignment of both the Entrance and Sand Island Ranges (Reference Section 5.1.4), the entrance channel tends to be subjected to a cross-current, a phenomenon observed during the 1959 current measurement program.

An additional influence observed in the course of the present study is a pronounced set to the southwest in the vicinity of

buoy No. 10 during the first few hours of the ebb. This current is produced by water exiting Baker Bay in the dredged channel west of Sand Island (Captain Martin West, June 1979, personal communication).

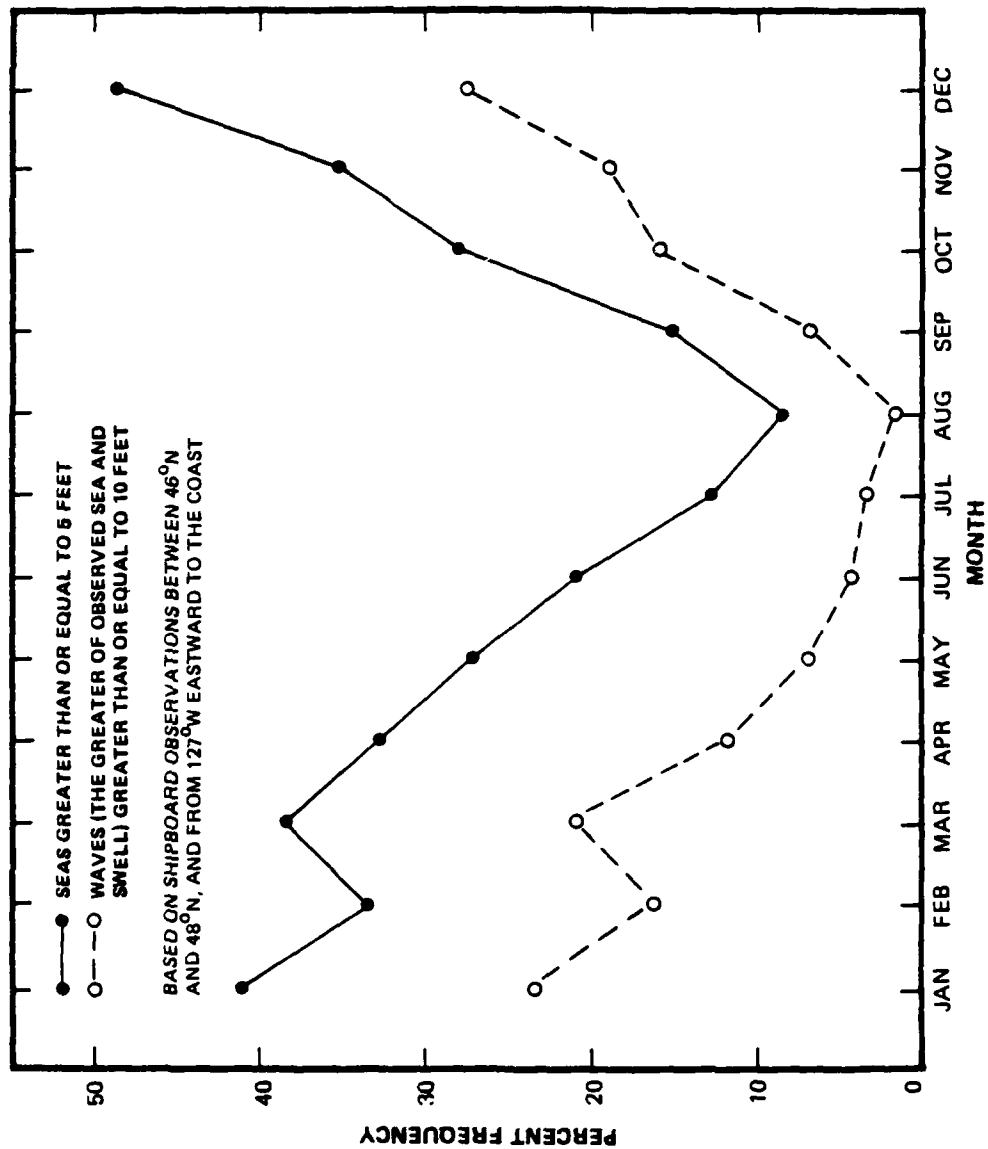
Outside the jettied portion of the entrance, the predominant east-west current orientation may undergo considerable modification under the influence of wind-driven currents.

Waves

Although direct, long term wave measurements at the Columbia River Entrance are lacking, the wave climate may be inferred from available deep water wave statistics. A statistical hindcast study for the years 1956 through 1958 prepared by National Marine Consultants, Inc. [11] includes data for a station located at 46°12'N, 124°30'W, approximately 14 nautical miles seaward of the Columbia River lightship. Additionally, observations made by ships in passage off the coast of Oregon and Washington are tabulated in the U.S. Naval Weather Service Command's Summary of Synoptic Meteorological Observations (SSMO) (May, 1976, Area 40).

It is evident from Figure 7, which is based on SSMO data, that both seas alone and the higher observed sea and swell are considerably more severe during the winter months. Low pressure systems moving eastward across the North Pacific create swell which generally approaches the study area from a northwest through westerly direction. In addition, storm systems passing in the immediate vicinity of the river mouth contribute rough seas which may occur concurrently with high swell conditions. In keeping with the orientation of prevailing winter winds, the predominant direction of winter seas is from the south.

During the summer months, the wave climate is significantly milder. Both sea and swell from the northwest quadrant predominant.



SOURCE: U.S. NAVAL WEATHER SERVICE
 COMMAND, MAY 1976
 SSMD, VOL. 6, AREA 40

FIGURE 7 - MONTHLY PERCENT FREQUENCY OF SEA HEIGHTS GREATER THAN OR EQUAL TO 5 FEET AND WAVE HEIGHTS GREATER THAN OR EQUAL TO 10 FEET

The average annual distribution of deep water wave heights based on both the SSMO and National Marine Consultants statistics is presented in Figure 8. Swell heights are displayed for the National Marine Consultants data, whereas the higher of observed sea and swell heights is plotted for the SSMO data. Sea and swell roses summarizing average annual deep water wave conditions compiled in the National Marine Consultants hind-cast are presented in Figures 9 and 10, respectively.

Local wave conditions at the bar may vary dramatically from offshore conditions due to the effects of refraction, shoaling, and currents. During periods of ebb tide, incoming waves are significantly steepened under the influence of the outbound current to the extent that breaking may occur across the entire entrance for waves which are non-breaking offshore. Conversely, during flood tide, the steepness of offshore waves tends to be reduced in the river mouth.

5.1.4 Navigational Considerations

Vessel Traffic

The Columbia River entrance is transited by deep-draft vessels bound to and from numerous ports and landings upriver, the principal of which are Portland and Astoria in Oregon, and Vancouver and Longview in Washington. As indicated in Table 4, which presents a summary of vessels using the entrance classified by draft, an annual average of 962 ships with a draft in excess of 30 feet transited the bar between 1971 and 1977. The river traffic consists primarily of oil and dry bulk carriers, auto and log carriers, and general and containerized cargo carriers.

Channel Configuration

The present entrance channel over the Columbia River Bar consists of two alignments linked by a 35° turn (Reference Figure

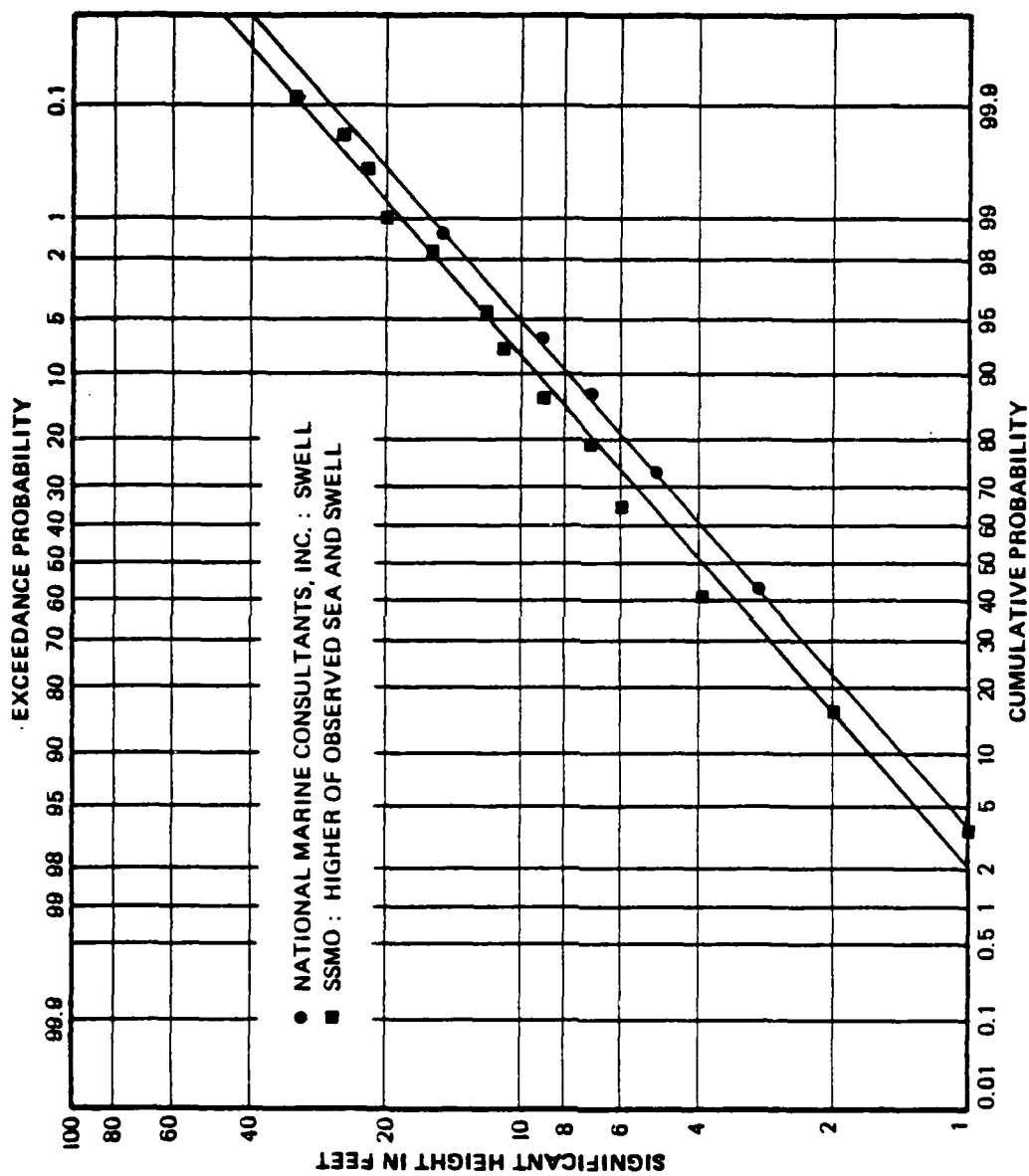
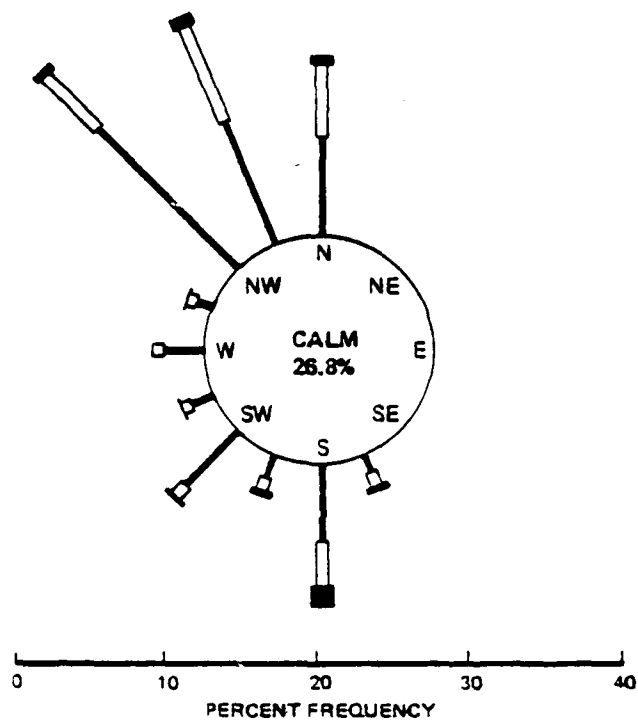


FIGURE 8 - AVERAGE DISTRIBUTION OF DEEP WATER WAVE HEIGHTS



SEA HEIGHT IN FEET SHOWN BY WIDTH OF LINES:

1 TO 4.9 FEET IS SHOWN THUS: 

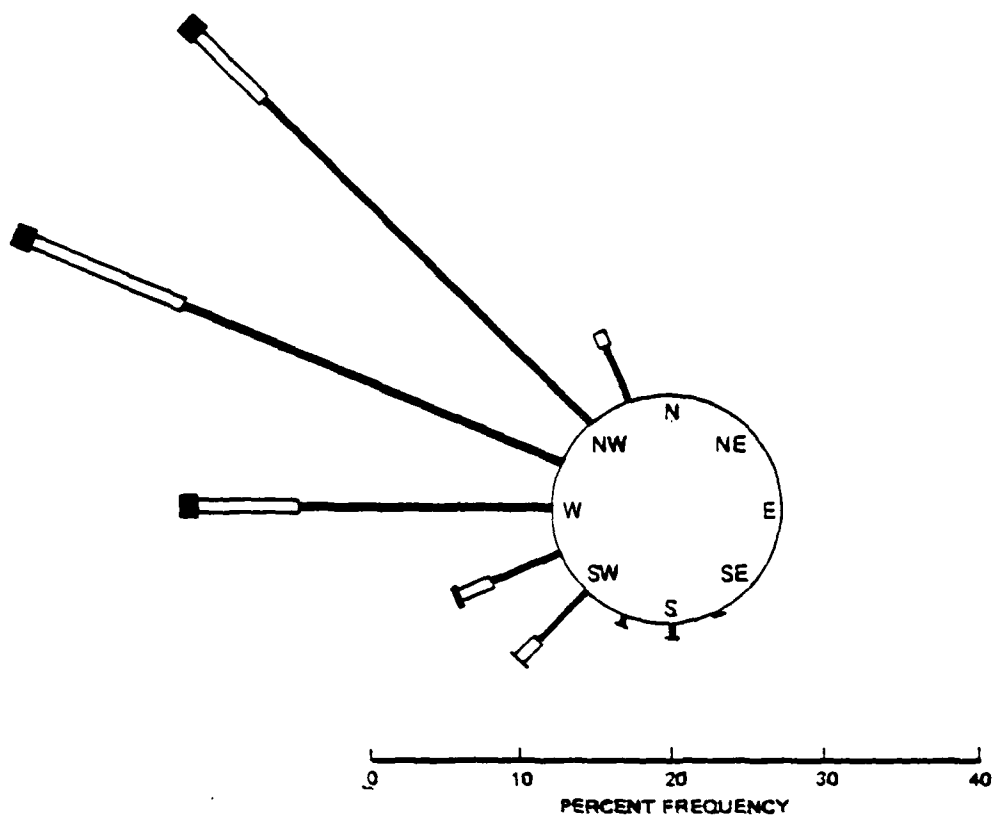
5 TO 10.9 FEET IS SHOWN THUS: 

11 FEET AND GREATER IS SHOWN THUS: 

BASED ON 3-YEAR HINDCAST FOR THE PERIOD
1956 - 1958 FOR 46°12'N, 124°30'W

SOURCE: NATIONAL MARINE CONSULTANTS, INC.

FIGURE 9 - DEEP WATER SEA ROSE



SWELL HEIGHT IN FEET SHOWN BY WIDTH OF LINES:

1 TO 4.9 FEET IS SHOWN THUS: ———

5 TO 10.9 FEET IS SHOWN THUS: ═════

11 FEET AND GREATER IS SHOWN THUS: █████

BASED ON 3-YEAR HINDCAST FOR THE PERIOD
1956 - 1958 FOR 46°12'N, 124°30'W

SOURCE: NATIONAL MARINE CONSULTANTS, INC.,

FIGURE 10 - DEEP WATER SWELL ROSE

TABLE 4
SUMMARY OF DRAFTS OF VESSELS USING COLUMBIA RIVER ENTRANCE

DRAFT (FT)	1971	1972	1973	1974	1975	1976	1977	7 YR-AV
30	145	196	234	202	168	161	178	183
31	175	166	229	161	144	173	187	176
32	199	235	248	194	201	202	206	212
33	83	132	113	145	145	213	203	148
34	48	64	73	85	100	160	149	97
35	26	43	45	95	70	94	91	66
36	21	43	33	49	56	52	51	44
37	12	15	20	33	23	24	20	21
38	3	4	7	13	16	18	7	10
39	0	3	2	6	9	4	4	4
40	0	0	4	0	0	0	0	1
TOTAL	712	901	1008	983	932	1101	1096	962

SOURCE: Waterborne Commerce of United States.

1). Approaching from seaward, the channel commences with the Entrance Range at an alignment of 045° True. From buoy No. 2, where the buoyed channel begins, to buoy No. 8, where the Entrance Range intersects with the Sand Island Range, the channel extends approximately 3.3 nautical miles. The Sand Island Range then marks mid-channel for a distance of approximately 1.4 nautical miles on a heading of 080° True. Proceeding upriver from the Sand Island Range, the channel makes a gradual turn toward a southeasterly alignment and narrows considerably to its river width of 600 feet. For the entire length of the entrance channel, which consists of the Entrance and Sand Island Ranges, the authorized project width and depth are 2,640 feet and 48 feet, respectively.

In order to stabilize the navigation channel, jetties were constructed on both sides of the entrance. The south jetty, begun in 1885, reached its ultimate length of 6.62 miles from Point Adams in 1913. Severe wave conditions subsequently reduced the elevation of the outer end of the structure to low-water level. The head of the superstructure was stabilized at its current position approximately 3,900 feet shoreward of the outer end of the jetty by placement of a concrete terminal block in 1941. The outermost portion of the south jetty thus provides only partial protection from southerly sea and swell (Reference Figure 1).

The original north jetty was constructed 2.35 miles in a southwesterly direction from Cape Disappointment between 1913 and 1917. With the exception of the outermost 1,500 feet, a short dog-leg to the west which has deteriorated, the jetty is presently in good condition.

Pilotage

Vessels wishing to cross the Columbia River Bar must be under the supervision of an officer licensed by the U.S. Coast Guard

with a specific pilotage endorsement for the Bar if they are: a.) a foreign registry, b.) of U.S. registry and bound to or from a foreign port, or c.) of U.S. registry, bound between U.S. ports, and in excess of 1,000 Gross Registered Tons.*

With the exception of a relatively small number of U.S. coast-wise vessels under the command of masters with pilotage endorsements, pilotage is provided by the Columbia River Bar Pilots, an association currently composed of 21 highly-experienced ship masters. Eligibility for the association is dependent not only on a federal pilotage endorsement but also on a master's license and master's experience. The pilotage boarding and debarking areas are located off Astoria, Oregon on the river end, and approximately 1 nautical mile east of the Columbia River Lightship on the seaward end of the bar pilotage ground.

Bar Closure

Primarily during the winter season, severe wind and wave conditions occasionally necessitate closure of the river entrance to all vessel traffic. Such closures, which are ordered at the discretion of the Bar Pilots, generally last for a period ranging from several hours to several days.

Bar closures are summarized in Table 5 for the calendar years 1971 through 1979, and the first four months of 1980. The aggregate duration of closures reached a high of 384 hours in 1971 and a low of 79 hours in 1978 with an annual average of 203 hours for the period of record. An average of 22 days per year were affected by bar closures, ranging from 43 in 1971 to 9 in 1978.

The predominant cause of bar closures is swell breaking across the entire width of the channel, rendering vessel passage unsafe. This occurrence is most prevalent during periods of

* Columbia River Bar Pilots, Personal Communication, June 1979

TABLE 5
SUMMARY OF BAR CLOSURES
FOR THE PERIOD 1971 THROUGH APRIL 1980

CALENDAR YEAR	AGGREGATE DURATION OF CLOSURES (HOURS)	NUMBER OF DAYS AFFECTED BY CLOSURES
1971	384	43
1972	179	23
1973	125	22
1974	245	31
1975	247	25
1976	133	11
1977	304	20
1978	79	9
1979	126	11
1980 (through April)	<u>63</u>	<u>5</u>
Annual Average	203*	22*

*Excluding 1980

Source: Columbia River Bar Pilots

ebb tide, when incoming waves are steepened to the point of breaking by the outgoing current. According to Captain Martin West of the Bar Pilots (personal communication, June 1979), a large majority of all bar closures is associated with a single ebb tide, lasting typically five to seven hours. During periods of particularly severe wave activity, however, the bar may remain closed due to breaking throughout the tidal cycle.

An additional, though infrequent cause of bar closures, is the extreme wind and sea conditions associated with passing storms. Particularly following the passage of a front, with resulting confused sea conditions, the transfer of pilots to and from the pilot boat may be precluded even though the channel is navigable. Such occurrences are typically of short duration.

5.2 ENVIRONMENTAL CONDITIONS DURING THE STUDY PERIOD

The environmental conditions observed from shipboard during each of the 53 bar transits have been presented in Table 1. Considered as a whole, the study period was marked by unusually calm wind and wave conditions. When asked to characterize the winters of 1978-1979 and 1979-1980, the Bar Pilots described the winter of 1979-1980 as relatively worse than 1978-1979, but both were mild as compared to previous winter seasons. Their judgment is well substantiated by Table 5, which lists data on bar closures for the period January 1971 through April 1980. During the years 1978 and 1979, the bar was closed to vessel traffic an average of 79 hours spread over 9 days for 1978 and an average of 126 hours spread over 11 days for 1979. This compares with an annual average of 203 hours and 22 days over the period of record.

A category-by-category account of the environmental parameters in Table 1 is presented in the following sections, along with a general assessment of their effect on vessel operations.

5.2.1 Weather

In general terms, weather conditions were mild during the 53 bar transits with an unusually low frequency of precipitation and no major storms. Precipitation was encountered on 16 occasions, with the remainder of the voyages approximately equally divided between fair and overcast conditions.

Monthly summaries of weather observations at Clatsop County Airport (Astoria, Oregon) are provided in Appendix E for the Phase I and II field periods. Appendix F contains the daily summary weather observations at the same station for the Phase I and II field periods for each of the 53 transit dates.

5.2.2 Visibility

Visibilities of 2 nautical miles or less were encountered on Voyage Nos. 19, 24, 29, and 38. During these transits, the pilots depended heavily upon radar due to the obscurement of the range lights and all but one or two channel buoys at a time. The worst visibility was encountered during Voyage 29, when dense fog often obscured the ship's bow from view. Even this transit, however, despite a few tense moments when passing another ship bound in the opposite direction, was rated as "easy" by the pilot in light of the calm wave conditions and relatively slack current. Owing largely to the quality of modern radar equipment, reduced visibility appears to pose a major problem only in concert with other adverse factors, such as waves, currents, and other traffic.

Visibility was impaired to a lesser extent on 16 other transits. When the visibility exceeded several miles, however, it was generally possible to sight several consecutive channel buoys even though the range lights were obscured for a portion of the crossing; other traffic in the channel was also discernible at a relatively safe distance. Under such conditions, radar and visual sightings were used in a complementary fashion and passage through the channel was not hindered to any large extent.

Even during transits with unlimited visibility, of which there were 33, the pilots frequently employed radar as an aid in locating channel buoys and other traffic.

Visibility observations taken at Clatsop County Airport on the date of each transit are in the weather data presented in Appendix F.

5.2.3 Winds

The wind conditions which prevailed during the 53 bar crossings conformed closely with the seasonal trends in direction discussed in Section 5.1.2. For the seven transits made during May and June 1978, winds blew exclusively from a northwesterly through westerly direction. Winds from the southeast quadrant were most frequent during the subsequent winter months of November through March. Speeds were generally low, with 31 transits conducted in winds of 10 knots or less. Of the 22 remaining transits, only seven were subjected to winds exceeding 15 knots.

The most severe wind condition encountered during the Phase I study was a 25 to 30 knot northwesterly during Voyage No. 14. Although this transit took place on an outbound tanker in the ballast condition, navigation of the vessel did not appear to be significantly affected by the direct influence of the wind. The resulting sea and current conditions, however, did combine with a moderate swell condition to produce a crossing rated as "moderate" by the pilot.

The most severe wind conditions encountered during the Phase II study were on Voyage Nos. 37, 38, and 44. Voyage Nos. 37 and 38 were both aboard the *Höegh Mascot*, a bulk carrier, going inbound and outbound, respectively. On Voyage No. 37 an east southeasterly wind was blowing at 30-35 knots with gusts to 45 knots. The strong wind combined with a weak ebb current resulted in the ship being set to the north side of the channel. On Voyage No. 38 a southerly wind was blowing at 40 knots with gusts to 50 knots. The strong wind, this time combined with a strong ebb current and developing seas of 6-10 feet, again caused the ship to be set to the north side of the channel. Even so, the pilots rated Voyage No. 37 as an "easy" crossing and Voyage No. 38 as a "moderate" crossing due to the combination of wind, current and developing seas. Voyage No. 44 was outbound aboard the

automobile carrier *World Wing*. Typical of automobile carriers, the *World Wing* has a large sail area and relatively shallow draft causing difficult steerage in crosswinds. The *World Wing* was the first ship out following a bar closure of approximately 6 hours. Winds were blowing from a westerly direction at 25-30 knots and gusting to 40 knots. The pilot boat *Peacock*, which was outside, radioed that the swell was 10-15 ft, short and sharp from the west. As the *World Wing* headed out, the combination of the wind, swell, and flood current set her down on the south side of the channel beginning around buoy No. 8. As a result she was crabbing north as much as 15° to maintain her course. The crossing was rated "moderate" by the pilot but he commented that no reduction from sea speed was required, which he thought was notable.

Although wind conditions may necessitate corrective action by the pilot, winds alone do not appear to significantly affect the safe navigation of the entrance channel.

Wind, sea and swell observations from the lightship *Columbia* at the approximate time of most transits for Phase I are compiled in Appendix G. Data for some transits were unavailable due to the lightship not being on station. Wind and preliminary wave spectra data at the approximate time of most transits for Phase II and some of Phase I are also compiled in Appendix G. These data are from gauges located near the Columbia River Entrance and are provided by the U.S. Army Coastal Engineering and Research Center. Additionally, wind observations at Clatsop County Airport are included in the weather data in Appendix F.

5.2.4 Seas

Sea heights, like wind speeds, remained small throughout most of the project and exerted little negative impact on vessel navigation. Seas greater than 2 ft were encountered on only 16 transits, with the highest seas of 6 to 10 ft associated

with the strong southerly winds already mentioned in connection with Voyage No. 38. For the entire project, Voyage No. 38 represents the only case where the sea conditions were higher than the swell conditions, which clearly played the major role in inducing vessel motions. From the project's point of view, it is unfortunate that no major storm systems with severe seas were encountered at the river mouth.

Sea heights and periods observed from the lightship *Columbia* for Phase I appear in Appendix G. Because the lightship *Columbia* was replaced by a lightbuoy in November 1979 there is no observed sea height data available for Phase II.

5.2.5 Swell

Although no major storm systems passed through the area during any of the bar crossings, relatively severe swell generated by distant storms was encountered on several occasions. Based on the pilots' observations and statistics on bar closures (reference Table 5), however, the swell conditions prevailing during the project must be characterized as unseasonably mild. It is apparent from Table 1 that the overwhelming majority of observed swell exhibited an 8 to 10 second period. Forty-two of the 53 transits recorded swell directions from northwest through west, with west the most prevalent orientation.

Swell conditions unquestionably exerted the most significant influence on vessel navigation in the entrance channel. Of the 10 bar crossings on which swell heights were observed to equal or exceed 10 ft, 8 were rated as "moderate" or "difficult" by the pilots. The other transits rated "moderate" (Voyage Nos. 14, 38, 50, and 52) experienced 8 to 10 ft swells except Voyage No. 38 which experienced the roughest sea conditions recorded during the project of 6 to 10 ft. A 10 ft wave height thus appears to constitute an approximate threshold

above which vessel navigation becomes considerably more difficult. This value may be modified to some extent by other environmental factors and ship characteristics (e.g., draft, speed, seakeeping abilities). On the two transits which were rated as "easy" despite swell heights in excess of 10 ft, for example, the other factors such as draft, visibility, and sea height were conducive to an untroubled passage (Voyage Nos. 9 and 22, both of which experienced 10 to 12 ft swell).

The roughest bar crossing, Voyage No. 15 on the inbound tanker *Hillyer Brown*, warrants amplification as an illustration of severe bar conditions. When the ship arrived at the pilot station in the early morning hours, the bar was closed due to a 15 to 20 ft westerly swell breaking across the entire entrance at the strength of the ebb tide. However, as the ebb flow subsided and breakers (visible on the ship's radar) became less frequent, the bar was opened and the *Brown* headed in on the entrance range several miles behind an auto carrier. With the westerly swell on the port quarter, the helmsman had difficulty holding his course, and frequently had the helm hard over in an attempt to maintain steerage. The problem was exacerbated by the presence of the auto carrier ahead, forcing the *Brown* to maintain a slower speed than desirable for steerage control.

When the waves became steeper and breakers more frequent between buoy Nos. 4 and 6, the ship broached on two occasions, swinging to the north nearly beam-on to the swell. On the second occasion a large wave broke directly against the hull, sending green water over the wheelhouse (approximately 50 ft above the waterline) and completely obscuring the deck below. Although no major damage was sustained, stanchions on the weather side were bent, doors and ports not securely dogged were breached, and a large searchlight was swept off the weather bridge wing. Once the ship recovered and made the jettied portion of the entrance, the remainder of the passage was uneventful. The bar was subsequently re-closed to vessel traffic.

Two additional transits, Voyage Nos. 16 and 19, experienced swell of up to 18 ft from the west. Because the ships were outbound in both cases, heading toward the swell, steerage was not a problem. The pilots were most concerned with the pitching motion, which they attempted to minimize by reducing speed. Once again, the roughest conditions were located between buoy Nos. 4 and 6. Breakers were infrequent and relatively weak, posing no danger to the vessels.

Swell observations from the lightship *Columbia* for Phase I in Appendix G show poor agreement with the shipboard observations in Table 1a. The lightship data are characterized by consistently shorter periods and lower swell heights. Preliminary wave spectra data (Appendix G) for Phase II show much better agreement with the shipboard observations in Table 1b.

5.2.6 Currents

The "Tidal Current" column of Table 1 is based solely on tidal current predictions (U.S. Department of Commerce, 1978, 1979 and 1980), and as such is intended only as a rough indication of prevailing conditions. Wind and discharge-induced currents are not considered. The designation "slack" is arbitrarily applied when the entire data acquisition period for a particular transit falls within one hour of the predicted slack water. A more detailed insight into current conditions is provided in Appendix H, where hydrographs of tide heights actually observed at Astoria for the 24 hour periods centered near the time of each bar crossing are presented. River discharge at Vancouver, Washington is also indicated for each transit date.

Actual current conditions during the transits were difficult to observe accurately due to the ship's speed and instances of reduced visibility. On several occasions, however, the time of slack water appeared to differ from the prediction. Due to the light wind conditions which prevailed during most of

the project transits, wind-induced currents were rarely detected. One of the most pronounced of these was associated with the 25 to 30 knot northwesterly on Voyage No. 14. Once the outbound *Chevron Colorado* cleared the jetties, she experienced a southerly set of approximately 3/4 knot.

Although currents at the river entrance necessitated frequent course corrections, they did not by themselves appear to create a severe hazard to navigation. In this regard, the experience of the pilots in anticipating and compensating for the effects of the current is of paramount importance. Modern shipboard radar is also a valuable asset in detecting position changes due to unexpected currents before they endanger the vessel.

The most significant impact of currents on vessel navigation occurs through the steepening and breaking of waves under the influence of the ebb current (reference Section 5.1.3). For wave heights under about 10 ft, current-induced steepening appeared to pose no problem to vessel operations. For higher waves, however, the presence of an ebb current created significantly more difficult transit conditions, particularly when it induced breaking.

6.0 DATA ANALYSIS

6.1 METHODOLOGY

As described in Section 2, there are basically five parameters directly measured through instrumentation. They are pitch, roll, heave acceleration, ship heading, and ship position. The actual procedure of sampling, classifying and analyzing these data will be detailed in the next section. In this section, some fundamental background to transform these basic data into the desired information is discussed.

The primary information required from the measurements are the variations of vertical and horizontal excursions of a ship passing through the entrance channel. This information will then provide the guidance for the channel depth and width design. The basic data obtained from these measurements, however, do not directly provide the desired information because the sensors measure only the motions at one fixed point on a ship. Nevertheless, the basic data can be used to determine the motions at any arbitrary location if a correct transformation procedure is applied. In general, it is always desirable that the sensors or the measuring devices are located as close as possible to the ship center of gravity so that the movements at other locations can be determined with minimum correction. In real cases, however, this is not often practical. For practical reasons, our measurements were taken at the navigation bridge with all the sensors located on the ship centerline whenever possible. It is evident that the largest movement at any instant occurs at one of several extreme points of a ship, for instance, the bow, the stern, or the bilge, the corner where the side hull meets with the bottom in the neighborhood of midships. In order to determine the motions at these locations, some algebraic manipulations of the basic data are required. In the following, the methods of obtaining the motions at these locations are outlined.

Vertical Motions

Three fundamental modes of motions affect the vertical movement of a ship; they are pitch, heave and roll. Pitch is an angular motion signifying the rise and fall of the bow and stern of a ship in a rough sea, heave is an up and down translational motion of the ship, and roll is an angular motion about the ship's longitudinal axis. Due to combined motions of pitch, heave, and roll, the largest vertical motion occurs normally at the bow, stern or bilge, as these three locations are the farthest points from the center of gravity (CG), the approximate center of movement in most cases. In most ships, the CG is located aft of the midship, and consequently, the bow normally has larger vertical motion than either the stern or the bilge. However, this is not always true. For instance, when the upward heave motion is in-phase with the bow down pitch motion, the stern movement would be larger than the bow, even if the CG is nearer to the stern. In other words, the phase angle between heave and pitch has as significant an effect as the motion amplitude on the total movement at various locations. Similarly, when roll motions are more significant than pitch motions, movements at the side or the bilge rather than those at the bow may be the controlling factor for the channel depth and bottom clearance.

Let $\theta_m(t)$, $z_m(t)$, and $\phi_m(t)$ be the pitch, heave and roll measurements at the sensor location (x_m, y_m, z_m) . A Cartesian coordinate system $0-x,y,z$ is considered, with its origin located at the ship CG, positive x toward the bow, y portside, and z upward. Angular motions are considered to be positive as follows: pitch down by the bow, roll to starboard, and yaw to port.

It should be noted here that $z_m(t)$ is not directly measurable from our instrumentation; only heave accelerations were actually measured. A double integration in time of the measured data is required to obtain $z_m(t)$. The method and procedure to perform these integrations will be discussed in Section 6.2.

After $\zeta_m(t)$ is obtained, the heave motion at the ship CG, $\zeta(t)$, can be calculated by

$$\zeta(t) = \zeta_m(t) + x_m \tan \theta(t) + R \{ \cos \beta - \cos [\beta + \phi(t)] \} \quad (1)$$

where

$$R = (y_m^2 + z_m^2)^{1/2}$$

$$\beta = -\tan^{-1} (y_m / z_m)$$

It is clear that there is no difference in angular displacements from one location to another so that $\theta(t) = \theta_m(t)$ and $\phi(t) = \phi_m(t)$.

The second term on the right-hand side of Equation (1) represents the correction of heave motion due to pitch and the third term the correction due to roll. It is noted that Equation (1) is derived on the basis that both the pitching and rolling axes are passing through the ship CG. For ships of ordinary form, the assumption for roll is well accepted [12], but the location of the pitching axis may vary from 0.04 to 0.16 of the ship's length abaft of the CG [7].

The operation shown by Equation (1) provides the transformation of the measured data to obtain the heave motion at the CG. The final objective is to obtain the largest vertical motion of the ship. Let the distance between the bow and CG be x_f , then the total vertical movement at the bow, h_f , can be evaluated as follows:

$$h_f(t) = \zeta(t) - x_f \tan \theta(t) \quad (2)$$

Similarly, if x_s is the x-coordinate of the stern, the vertical excursion at the after end of the ship, h_a , is

$$h_a(t) = \zeta(t) - x_s \tan \theta(t) \quad (3)$$

Aside from the bow and stern which may have an extreme movement due to a combined motion of pitch and heave, a large vertical excursion may occur at the side of the ship hull due to a combined motion of heave and large roll oscillations, and consequently, create critical bottom clearance at the bilge. If the extreme beam width of the ship is B, then the vertical excursion at the side or the bilge is approximately given by

$$h_s(t) = \zeta(t) \pm \frac{1}{2}B \tan \phi(t) \quad (4)$$

where the upper sign is for the portside excursion and the lower sign is for the starboard.

Horizontal Motions

There are two kinds of horizontal motions which are relevant to our analysis. One is the sideways translational movement of the entire ship, which is normally known as sway. The other is an angular oscillatory motion of the bow and stern and is called yaw. These two motions combine to determine the total sideways excursion of a ship underway. There is another mode of horizontal motion--surge, which signifies the fore and aft, translational, oscillatory motion normally generated by the imbalance of propulsion power and ship resistance due to various disturbances, for instance, waves. Since this component has little affect on either the width or the depth requirement of a navigational channel, no measurement of this component was considered.

The information on horizontal motions is obtained from analysis of the measurements of ship heading and trajectory track. In principle, by comparing the recorded trajectory track with the intended path, the maximum sideways excursion from the intended

path is evaluated to represent the maximum sway for a ship passing through a given length of the channel. Similarly, comparing the recorded ship heading with the trajectory course determines the instantaneous yaw angle. If L is the length of the ship, from the information on yaw data, $\psi(t)$, the projection of the ship length on a cross vessel-track plane is given by

$$b(t) = L \sin \psi(t) \quad (5)$$

By assuming the ship as a rectangular box of length L and beam B , the total effective projection width can also be determined through elementary geometry. This information together with the tracking deviation, or the sway as defined above, provides the total sideways excursion, which will be detailed in Section 8.2.

Statistical Analysis

From the foregoing discussion, it is understood that there are six fundamental parameters available for analysis among which pitch and roll are directly from measurements, and heave, bow, stern, and vertical side motions are derived from the original motion measurements. Each of these data is in the form of a time history of a fluctuating quantity. In order to describe data of this sort, two important aspects must be characterized: (a) the amplitudes of the oscillations, and (b) the frequencies which they contain.

Three characteristic amplitudes were processed for each sample of record: (a) maximum amplitude, (b) average amplitude, and (c) the root-mean-square (rms) amplitude. The detailed procedure will be shown in Section 6.2. The individual amplitudes were also ranked according to their magnitude so that the frequency of occurrence was determined and a cumulative frequency curve was developed for each sample of data. In addition, the

number of oscillations of each parameter was counted and the average period was evaluated.

With these data on hand, it has been hoped that some analytic functions can be fitted to the data and a test of significance be applied, so that certain statistical predictions and conclusions can be reached with confidence on the basis of the available data.

In general, ship motions, as well as ocean waves, under a given set of conditions can be described in terms of their distribution functions. There is considerable evidence [7, 8], indicating that the amplitude oscillations of a ship under a given sea condition obey the Rayleigh distribution law which is defined as

$$p(x) = \frac{2e}{E} e^{-x^2/E} \quad x \geq 0 \quad (6)$$

where $p(x)$ is the probability density of x

x is the variate

E is the mean value of the squares of x , namely $(x_{rms})^2$.

The cumulative distribution function is defined as the probability of a single variate being less than a given value x_i , mathematically:

$$P(x_i) = \int_0^{x_i} p(x) dx \quad (7)$$

or

$$P(x_i) = 1 - e^{-\left(x_i/x_{rms}\right)^2} \quad (8)$$

The probability of the variate to exceed x_i is then

$$Q(x_i) = 1 - P(x_i) = e^{-\left(x_i/x_{rms}\right)^2} \quad (9)$$

It is well known that the Rayleigh distribution is the asymptotic case of a very narrow spectrum [13]. While many of the records obtained during our measurements are not narrow-banded, still it will be shown that in most cases the Rayleigh law can be used to estimate a number of parameters; thus some statistical judgments can be made.

The Rayleigh distribution law is probably appropriate to describe a single event under a given condition. In order to draw some statistical conclusions from long term observations other analytic distributions have been tried and fitted. An attempt to fit the entire collected data into a logarithmic normal distribution has been tried and found successful. A log-normal distribution is defined as

$$p(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\log x - \xi)^2}{2\sigma^2}} \quad (10)$$

$$\text{and } P(x_i) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u_i} e^{-\frac{u^2}{2}} du, \quad \text{with } u = \frac{\log x - \xi}{\sigma} \quad (11)$$

where ξ is the mean value of $\log x$ and σ^2 is the variance of $\log x$.

6.2 PROCEDURES

The actual raw data recording took place approximately as the ship traveled between buoy No. 2 and Jetty A just inside the river. Time for the ship to travel this distance is approximately one-half hour. During this period the ship motions were monitored and recorded 5 times/second on a data cartridge.

At the field office the raw data were edited and transferred from the data cartridge to Hewlett Packard flexible disks for analysis and plotting on Hewlett Packard 9845 and 9830 computers at the home office. Editing consisted of looking for and marking any data gaps.

The actual data recording times for the entire 53 voyages are summarized in Tables 6a and 6b. In addition to the recording time, the data processing time is shown, which is the time interval within the recording time for which the data analysis applies. These times can be correlated with the ship track plots in Appendix A to visualize the ship's location. To the extent possible, the analysis was performed for that segment of data for which the ship was between buoy Nos. 2 and 8. On several outbound voyages, however, the data recording was terminated prior to reaching buoy No. 2 so as not to reflect course and speed changes related to discharging the pilot. Table 6 does not apply to the yaw data analysis as it is processed independently as will be discussed later.

The data analysis consists of the following: Computation of heave displacement from heave acceleration, computation of the excursion at the bow, stern and side due to heave, pitch, and roll, statistical analysis of the motions and excursions, time series and cumulative frequency plots of the motions and excursions, yaw and sideways excursion analysis, and plots of the ship track through the channel. Following is a discussion of the procedures used in the above mentioned analysis.

Computation of Heave Displacement and Excursions

Let $\ddot{z}_m(t)$ be the heave acceleration at the sensor location (x_m, y_m, z_m) . Analytically, this time history data can be expressed as follows:

TABLE 6a
TIME INTERVALS OF DATA RECORDING
AND DATA PROCESSING FOR EACH TRANSIT
(PHASE I)

VOYAGE NO.	RECORDING TIME		TOTAL RECORDING TIME	PROCESSING TIME		TOTAL PROCESSING TIME	REMARKS
	BEGINNING	END		BEGINNING	END		
1	20:49:00	21:14:36	25m 36s	20:49:00	21:03:00	14m 00s	No heading data
2	15:29:00	15:52:59	23m 59s	15:29:00	15:41:30	12m 30s	No heading data
3	19:04:01	19:27:29	23m 28s	19:04:01	19:15:01	11m 00s	No heading or position data
4	16:58:00	17:23:48	25m 48s	17:07:00	17:20:00	13m 00s	No heading data
5	12:01:03	12:24:59	23m 56s	12:02:03	12:15:45	12m 42s	No heading data
6	09:44:02	10:18:00	33m 58s	09:53:02	10:06:02	13m 00s	No heading data
7	21:38:05	22:02:00	23m 55s	21:48:05	21:59:35	11m 30s	No heading data
8	13:50:00	14:16:58	26m 58s	13:50:00	14:08:00	18m 00s	No position data
9	08:56:00	09:19:02	23m 02s	09:04:13	09:19:02	14m 44s	
10	05:15:00	05:37:59	22m 59s	05:15:00	05:29:30	14m 30s	
11	14:26:01	14:45:03	19m 02s	14:33:31	14:45:03	11m 32s	
12	13:13:00	13:38:59	25m 59s	13:14:00	13:30:00	16m 00s	
13	05:24:00	05:50:59	26m 59s	05:25:00	05:41:30	16m 00s	
14	15:21:00	15:48:58	27m 58s	15:31:00	15:48:58	17m 58s	No position data
15	05:38:00	06:11:58	33m 58s	05:39:36	06:04:30	24m 54s	DATA GAP FROM 06:02:33 to 06:02:40
16	14:36:30	15:09:59	33m 29s	14:43:00	15:09:59	26m 59s	
17	23:44:03	00:04:56	20m 53s	23:46:03	23:57:03	11m 00s	DATA GAP FROM 00:45:45 to 00:49:05
18	06:43:04	07:09:01	25m 57s	06:48:04	06:58:34	10m 30s	
19	07:14:09	07:46:59	32m 50s	07:21:09	07:40:09	19m 00s	
20	00:31:17	00:49:59	18m 42s	00:31:17	00:42:17	11m 00s	
21	07:44:00	08:05:56	21m 56s	07:47:00	07:58:00	11m 00s	
22	05:13:03	05:42:56	27m 53s	05:23:03	05:33:03	10m 00s	
23	23:12:02	23:32:58	20m 56s	23:17:02	23:27:02	10m 00s	
24	09:39:08	09:56:57	17m 49s	09:39:08	09:52:08	13m 00s	
25	21:42:00	22:22:58	20m 58s	21:42:00	21:54:30	12m 30s	No position data
26	12:33:00	12:49:57	16m 57s	12:37:00	12:45:00	8m 00s	
27	23:05:00	23:25:58	20m 58s	23:05:00	23:18:36	13m 36s	
28	04:33:00	04:56:57	23m 57s	04:34:00	04:49:30	15m 30s	
29	08:35:02	09:09:58	34m 56s	08:44:44	09:09:58	25m 14s	

TABLE 6b
TIME INTERVALS OF DATA RECORDING
AND DATA PROCESSING FOR EACH TRANSIT
(PHASE II)

VOYAGE NO.	RECORDING TIME		TOTAL RECORDING TIME	PROCESSING TIME		TOTAL PROCESSING TIME	REMARKS
	BEGINNING	END		BEGINNING	END		
30	08:12:00	08:34:00	22m 00s	08:13:30	08:27:30	14m 00s	
31	16:51:01	17:13:01	22m 00s	16:59:01	17:13:01	12m 00s	
32	04:55:00	05:15:50	20m 50s	05:03:00	05:15:50	12m 50s	
33	20:21:06	20:45:53	24m 47s	20:24:06	20:39:24	15m 18s	DATA GAP FROM 20:43:36 to 20:43:39
34	22:50:01	23:13:05	23m 04s	22:57:01	23:13:05	16m 04s	
35	05:41:17	06:08:59	27m 42s	05:45:47	06:08:59	23m 12s	
36	09:12:16	09:37:00	24m 44s	09:15:16	09:29:16	14m 00s	
37	21:14:00	21:35:56	21m 56s	21:14:00	21:29:30	15m 30s	
38	14:48:00	15:15:58	27m 58s	14:54:00	15:18:00	24m 00s	No pitch, roll, or acceleration data
39	08:51:28	09:15:00	23m 32s	08:52:28	09:07:28	15m 00s	Clock was inadvertently advanced ~ 1 hour at 08:55:34. End of re- cording time is approx- imate.
40	09:26:00	10:01:03	35m 03s	09:42:48	09:57:00	14m 12s	
41	11:55:00	12:15:37	20m 37s	11:55:00	12:07:00	12m 00s	No position data
42	08:34:01	08:58:55	24m 54s	08:34:31	08:48:31	14m 00s	
43	13:51:00	14:11:58	20m 58s	13:51:00	14:03:48	12m 48s	
44	13:33:01	14:08:57	35m 56s	13:45:01	14:08:57	23m 56s	
45	05:31:00	05:58:00	27m 00s	05:31:00	05:46:00	15m 00s	No position data
46	00:30:08	00:54:57	24m 49s	00:39:38	00:54:57	15m 19s	
47	17:29:01	17:54:58	25m 57s	17:29:01	17:42:01	15m 00s	
48	21:28:00	21:56:00	28m 00s	21:29:36	21:46:00	16m 24s	
49							No data
50	13:34:00	14:01:59	27m 59s	13:43:30	14:01:30	17m 00s	
51	10:44:00	11:07:57	23m 57s	10:44:00	10:59:12	15m 12s	
52	16:34:00	17:07:58	33m 58s	16:34:00	16:52:30	18m 30s	
53	23:01:01	23:28:59	27m 58s	23:02:31	23:17:01	14m 30s	

$$\ddot{\zeta}_m(t) = A_0 + \sum_{i=1}^{\infty} (A_i \cos \omega_i t + B_i \sin \omega_i t) \quad (12)$$

where the A's and B's are Fourier series coefficients to be determined, $\omega_i = 2\pi i/T$ and T is period. Because the ship experiences no net acceleration the constant A_0 can be set equal to zero. The coefficients A_i and B_i can be computed as follows:

$$A_i = \frac{2}{T} \int_{t=t}^{t+T} \ddot{\zeta}_m(t) \cos \omega_i t \, dt \quad (13)$$

$$B_i = \frac{2}{T} \int_{t=t}^{t+T} \ddot{\zeta}_m(t) \sin \omega_i t \, dt \quad (14)$$

Equations (13) and (14) can be solved by numerical integration using Simpson's rule for a finite number of terms.

Likewise an equation for the heave displacement at the sensor can be written as follows:

$$\zeta_m(t) = a_0 + \sum_{i=1}^{\infty} (a_i \cos \omega_i t + b_i \sin \omega_i t) \quad (15)$$

where again the constant a_0 can be set equal to zero because the ship experiences no net displacement and the constants a_i and b_i can be computed directly using the following relations:

$$a_i = - \frac{A_i}{\omega_i^2} \quad (16)$$

$$b_i = - \frac{B_i}{\omega_i^2} \quad (17)$$

Thus by integrating Equations (13) and (14) and evaluating Equations (16) and (17) the displacement for a data segment of period T is completely described by Equation (15).

In actual processing, data of accelerations were divided into 8-second segments. Using the above technique the entire acceleration record was converted to a displacement record segment by segment. To avoid end effects the first and last second of each 8-second segment were neglected when the displacement was computed. Therefore, each segment evaluated must overlap the previous segment by 2 seconds.

Once $\zeta_m(t)$ has been computed by the above procedures, the heave at the ship's CG and the excursions of the bow, stern and side can be computed by the methodology outlined in Section 6.1.

The above computations were performed on the Hewlett Packard 9845 Desktop Computer. The HP9845 has two internal digital cassette tape drives and both are utilized. Raw data are sequentially read from the flexible disk into computer memory, computations performed and results stored in numerical format on the cassettes. One of the cassettes stores the pure motions pitch, roll, acceleration and the time of day, while the second cassette stores the results of the computed heave at the ship's CG and excursions of the bow, stern and side. The data are stored in a convenient format for statistical analysis and plotting.

Computation of Statistical Parameters

The statistical analysis as discussed herein applies to the pitch, roll, heave acceleration, heave at the CG, and excursions of the bow, stern and side. Yaw and sideways motions are discussed separately. The statistical parameters of interest are the mean line deviation from zero, the maximum, average, and rms amplitudes, the number of variations and the average period. In addition, the necessary information to plot cumulative frequency is computed. The mean line deviation for pitch and roll corresponds to the static trim and list, respectively. For linear motions, this value is zero or small within record-

ing and processing accuracy. All the processed amplitudes including maximum, average, and rms are referred to the mean line.

The statistical analysis was performed on the HP9845. Once again the data were sequentially read into the computer memory from the cassette data tapes and computations made. The final results of the statistical analysis were output both in tabulated form on the HP9845 internal printer and stored on a third data tape for use in drawing the time series and cumulative frequency plots.

As previously mentioned, data were recorded between buoy No. 2 and Jetty A just inside the river. All of these data were used in plotting the ship's track through the channel. However, the portion of the data between buoy No. 8 and Jetty A is of no particular interest due to the relatively calm water condition in this area. Therefore, so as not to bias the statistical results, only that portion of data between buoy No. 2 and 8 was analyzed. The data analysis beginning and ending time is controlled by the user who inputs these times into the computer. The actual beginning and ending time was determined from the ship track plots (see Appendix A) and has been presented in Table 6.

Let $x(t)$ represent any one of the ship motions or excursions. The following formulae were used in the statistical analysis:

$$\text{mean deviation from zero} = \bar{x} = \frac{\sum_{i=1}^N x(t_i)}{N} \quad (18)$$

$$\text{average amplitude} = \frac{\sum |\text{peak amplitude}|}{N_p} \quad (19)$$

$$\text{rms amplitude} = \left[\frac{\sum (\text{peak amplitude})^2}{N_p} \right]^{1/2} \quad (20)$$

where N = total number of data points

N_p = total number of peaks.

The peak amplitude values used in the above equations are computed as follows: Given the mean line deviation from zero, \bar{x} , the algebraic sign and value of $\Delta x = x(t_i) - \bar{x}$ changes every one-half cycle and the peak amplitude for that half cycle is the maximum value of Δx . Every time the sign changes the peak amplitude value is reset to zero and the process repeats. The largest of the processed peaks is defined as the maximum amplitude.

Because the data contain some lower level noise in addition to the actual recorded signal, only values larger than a specified lower limit are counted when processing the peak amplitudes. A truncation factor of 0.2 deg is used for angular motions and 0.2 ft for linear excursions. Therefore, if the peak amplitude is less than the truncation factor it is not considered a peak. This eliminates counting false peaks.

Given the total number of peaks, N_p , the average period, T , is defined to be:

$$T = \frac{\text{length of record in seconds}}{N_p/2} \quad (21)$$

Time Series and Cumulative Frequency Plots

Time series and cumulative frequency plots were drawn on the internal printer of the HP9845. The plotting program offers the user the option of automatically plotting time series and cumulative frequency plots for all motions and excursions or

selectively plotting time series or cumulative frequency plots for individual motions or excursions. In addition the user may choose to plot any portion of the time series on an expanded scale by simply inputting the beginning and ending time desired.

The time series plots represent all of the data recorded from beginning to end, not just the portion of data that is statistically analyzed. Data were read from the cassette data tapes and plotted just as it was recorded or computed. For this reason the pitch and roll plots are not necessarily symmetric around the zero axis, because the ship may have had a trim or list.

Cumulative frequency plots were drawn as follows. During the statistical analysis the peak amplitudes were computed and stored in an array as was the number of peak amplitudes. The peak amplitudes were then grouped according to magnitude and the number of peaks within each group was counted and stored in a new array. The percentage of peaks within each group was then computed by dividing the number of peaks in each group by the total number of peaks and multiplying by 100. The cumulative frequency plot is then generated using the above percentages.

Special Considerations

On several occasions it was necessary to give special consideration to the analysis of the data as it did not readily lend itself to computer analysis in its raw form. Special consideration was given to the data on voyages when the wave conditions were so mild that the pitch data was of small amplitude and irregular (Voyage Nos. 39, 42, 43, 45, 47, 53) and on voyages when the pitch data was heavily contaminated with noise (Voyage Nos. 43, 44, 45, 46). For Voyage Nos. 39, 42, 43, 45, 47, and 53 the pitch correction term, $x_m \tan \theta(t)$, in equation (1) was not considered so that heave amplitudes at the measured location, ζ_m , are actually computed and tabulated. For Voyage

Nos. 43, 44, 45 and 46 the statistical analysis of the time series record had to be done manually due to the noise contamination of the data and it should be noted that the time series plots for these voyages, as shown in Appendix A, includes the noise.

Ship's Heading and Ship's Track Plots

The yaw analysis was based on the time series plot of the ship's heading and the plot of the ship's track through the channel. Data for these plots from the gyrocompass and positioning system were read directly from the flexible disk and stored on a cassette tape for plotting.

The time series plot of the ship's heading was plotted on the HP9845 internal printer as previously described.

Some data manipulation was necessary to plot the ship's track. As discussed in Section 2.4, the positioning system data is in terms of two ranges. These ranges must be trilaterated to determine the position of the ship in terms of north and south state plane coordinates. Once the ranges have been converted to state plane coordinates the ship track can be plotted.

The trilateration computation was done on the HP9845. Position data was sequentially read from the HP9845 data tape, converted to state plane coordinates and finally transferred to the HP9830A calculator and stored on an HP9830A data tape for plotting.

The ship track plots as shown in Appendix A are generated with the HP9830A and HP9862A Calculator Plotter. The shore and dredged channel outline were digitized and permanently stored on an HP9830A data tape to be used with the position data for a particular voyage. The plotting routine then draws plots as shown. The small tick marks on the ship track are placed

at one minute intervals while the larger tick marks are every five minutes. The tick marks allow one to correlate the time series plots and the ship's position in the channel.

Calculation of Yaw Motions

Due to the nature of the yaw motions the analysis must be confined to the portion of the channel for which the ship holds a steady course. That portion of channel was determined from the ship track plot and falls somewhere between buoy Nos. 2 and 8.

The yaw analysis program, which is run on the HP9845, computes the average and maximum yaw angle from the ship's heading data as follows. Let $\Psi(t)$ represent the yaw. The average yaw amplitude, $\bar{\Psi}(t)$, is computed from the peak to peak variations according to the relation:

$$\bar{\Psi}(t) = \frac{\sum |\text{angular variations between successive peaks}|}{2N_p} \quad (22)$$

where N_p = number of peak to peak values.

The peak to peak variations were computed from the ship's heading data as follows. A peak in the data is defined to be that point in the data where the algebraic sign of the difference in two successive data points changes from that of the previous point. For example, if $(\Psi_i - \Psi_{i-1})$ is positive and $(\Psi_{i+1} - \Psi_i)$ is negative then Ψ_i corresponds to a peak value in the data. The peak value is then stored until the next peak value is found and the peak to peak value is then defined to be the absolute value of the difference in the two peak values. As the peak to peak values are computed they are counted and stored in an array for later statistical analysis. Results of the yaw analysis were output on the HP9845 internal printer in tabulated form and also stored on tape.

7.0 VERTICAL VESSEL MOTIONS

7.1 SUMMARY OF DATA

As detailed in Section 6, for each voyage time history plots of pitch, roll, heave, and vertical bow, stern and side excursions were obtained to form the fundamental data base for vessel motion analysis. To show as an example, the plots of these variables for Voyage No. 9 are given in Figure 11. The data on each plot span over 23 minutes and 02 seconds, which corresponds to the total recording time during Voyage No. 9 beginning approximately from the location of buoy No. 11 and ending at the vicinity of buoy No. 2. The actual ship track plot obtained from the Mini Ranger data is shown in Figure 12. On this plot, tick marks corresponding to one minute intervals are superimposed over the tracking trajectory so that time and location can be conveniently correlated. One may notice that all motions are significantly less inside buoy No. 8, by simply examining the time histories together with the ship track plot.

It is noted that there is a distinct shift of mean zero in both pitch and roll records. This shift in the pitch record signifies the trim and that in roll corresponds to the list the ship had at the time of transit.

As described also in Section 6, a statistical procedure has been established so that several significant values such as the maximum, the average and the root-mean-square (rms) amplitudes are processed and a cumulative frequency plot is generated for each motion variable. Figure 13 shows as an example the cumulative frequencies of four of the variables mentioned above for Voyage No. 9. It is understood that these cumulative frequencies are plotted in terms of percentage to exceed a given motion amplitude.

A summary of the vertical-mode motions for vessels monitored over the entire period of the study is given in Table 7. Like

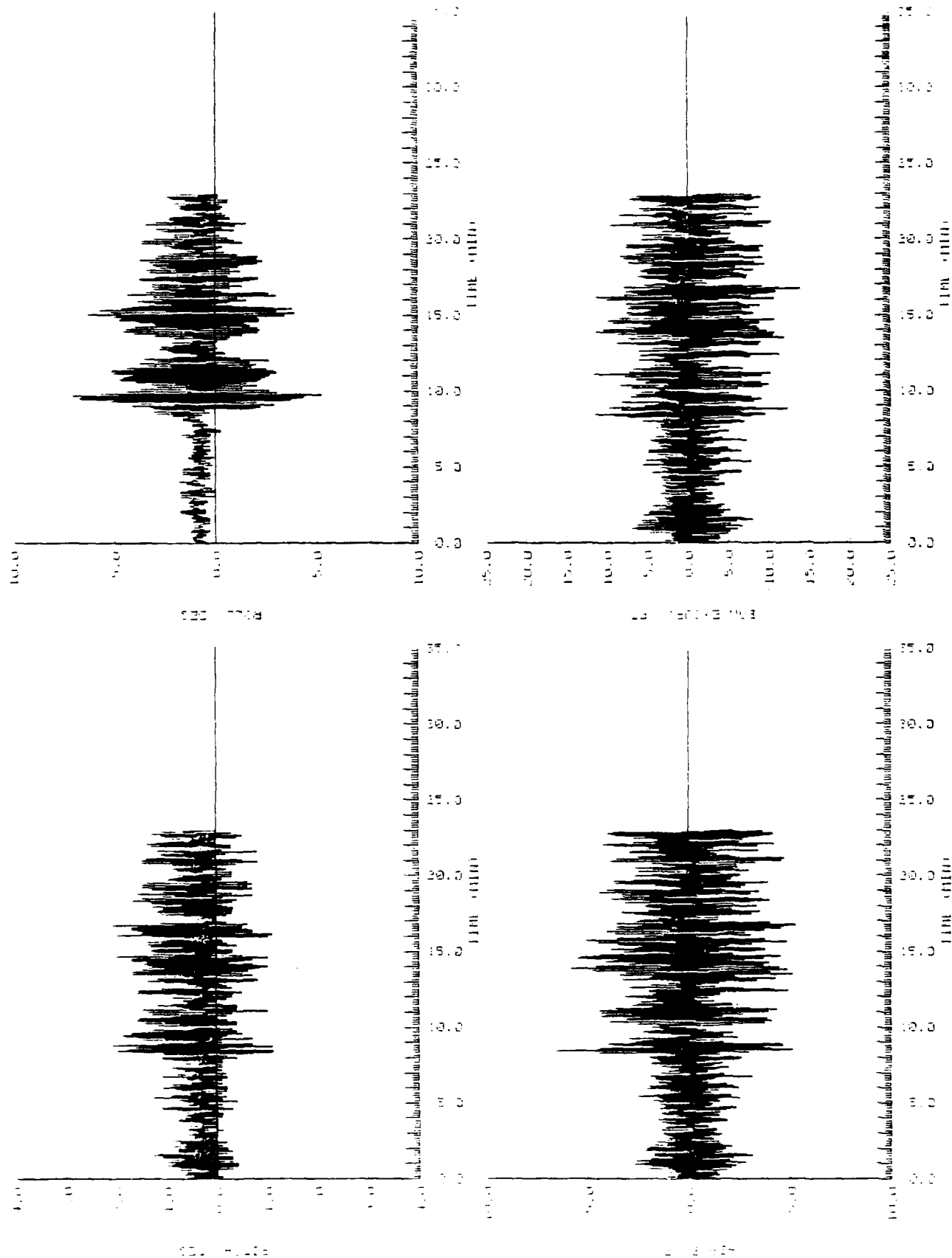


FIGURE II - SAMPLE TIME SERIES PLOTS (VOYAGE NO. 9)

VOYAGE NO. 09 SHIP TRACK

SCALE 1: 20000

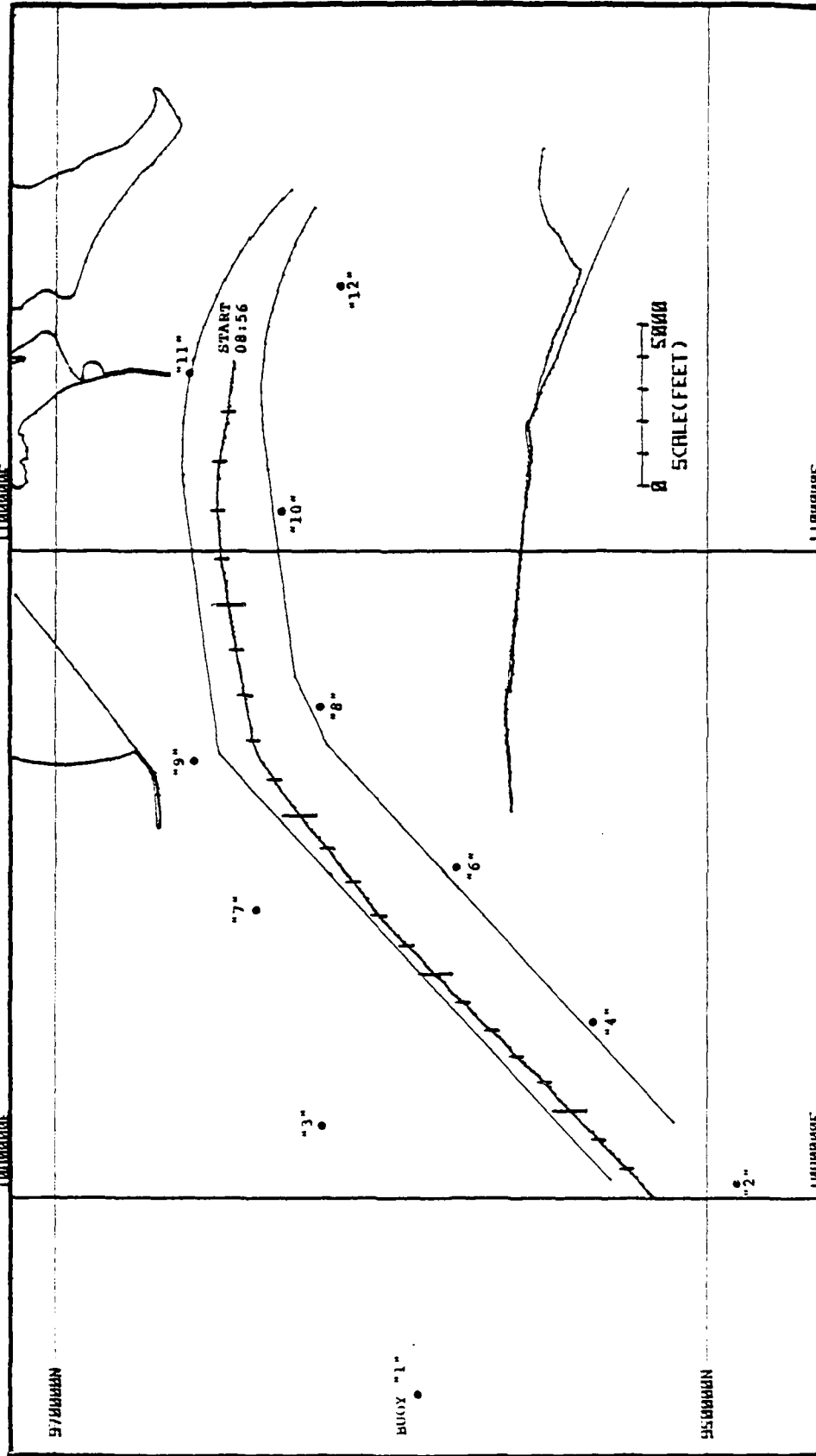


FIGURE 12 SAMPLE SHIP TRACK PLOT (VOYAGE NO. 9)

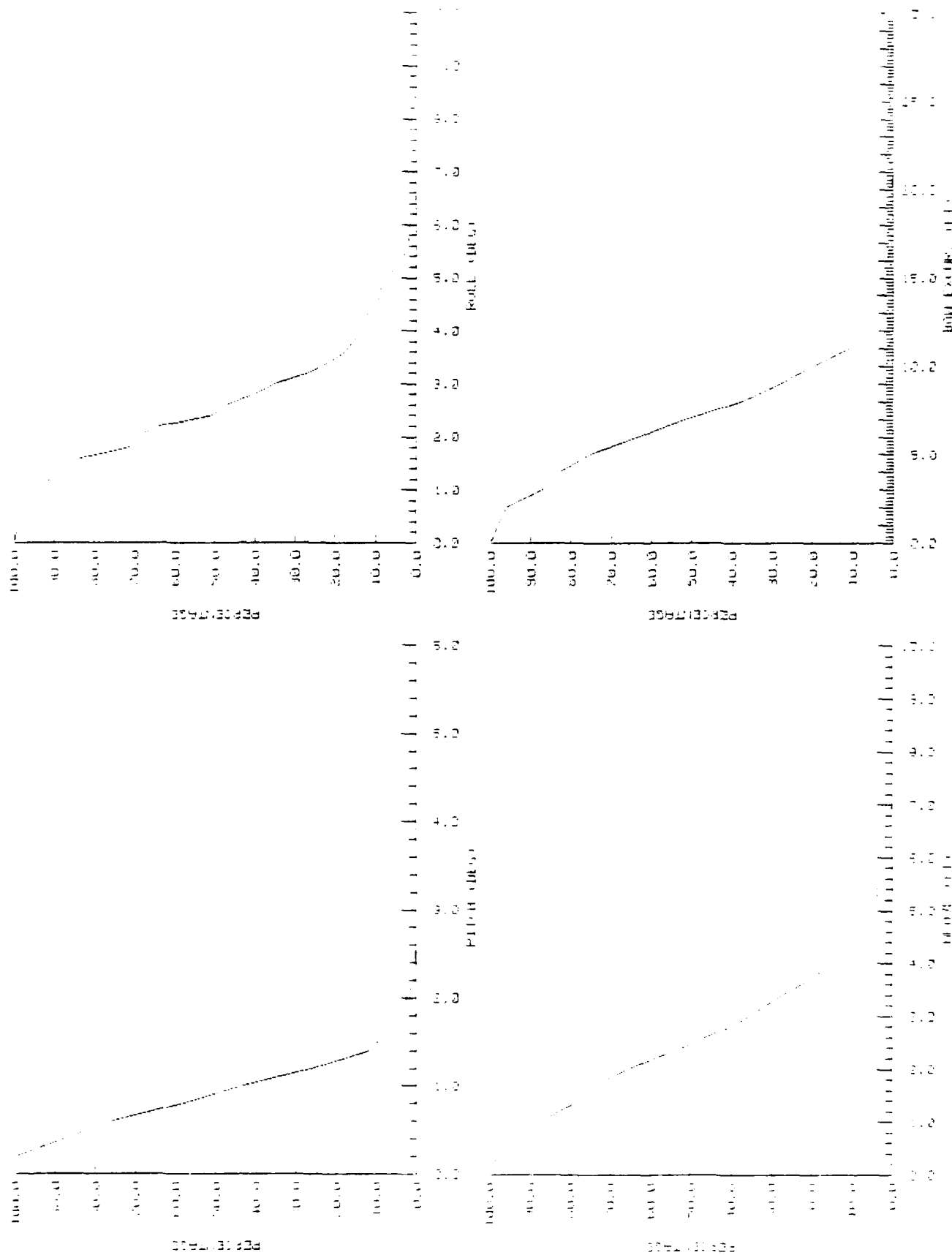


FIGURE 13 - SAMPLE CUMULATIVE FREQUENCY PLOTS (VOYAGE NO. 9)

AD-A098 983

TETRA TECH INC PASADENA CA

F/8 13/10

COLUMBIA RIVER ENTRANCE CHANNEL DEEP-DRAFT VESSEL MOTION STUDY (U)

SEP 80 S WANG, M KIMBLE, C BUTCHER, G D COX

DACW57-78-C-0028

UNCLASSIFIED

TETRAT-TC-3925

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TABLE 7a
SUMMARY OF VERTICAL MODE MOTIONS
(PHASE I)

VOYAGE NO.	DATE	VESSEL		TRANSIT DIRECTION	VESSEL MOTIONS (Amplitude)				VERTICAL MOVEMENT AT VARIOUS PORTIONS OF SHIP								MAXIMUM VESSEL PENETRATION			PILOT'S RATING OF MATING OF TRANSMIT
		NAME	TYPE		PITCH (DEG)	ROLL (DEG)	HEAVE (FT)	BOB (FT)	MAX UP	MAX AVER-AGE	DOWN	MAX UP	MAX AVER-AGE	DOWN	MAX UP	MAX AVER-AGE	DOWN	AMPLITUDE (FT)	PORTION OF SHIP	
1	5/20/78	CHEVRON LOUISIANA	OIL CARRIER	IN	2.5 0.9	6.4 2.7	7.0 2.6	20.2 17.0	7.3	7.4	7.6	3.2	9.0 3.7	49.5	BOW	6-8	EASY			
2	5/29/78	CHEVRON ARIZONA	OIL CARRIER	IN	1.3 0.6	2.9 1.1	3.6 1.6	8.9 10.4	4.2	3.8	3.1	1.5	4.3 1.8	43.8	BOW	2-4	EASY			
3	6/05/78	MOGHE MALLARD	BULK CARRIER	IN	0.7 0.3	1.4 0.6	2.8 1.1	6.3 5.7	2.6	2.1	1.7	0.9	2.5 1.0	29.3	STERN	*	EASY			
4	6/07/78	MOGHE MALLARD	BULK CARRIER	OUT	1.0 0.4	1.3 0.4	4.1 1.5	9.5 8.1	2.8	1.7	1.8	0.8	4.1 1.4	31.3	BOW	2-4	EASY			
5	6/21/78	CHEVRON OREGON	OIL CARRIER	IN	1.5 0.7	3.8 1.6	4.7 2.0	12.6 11.8	4.6	4.9	4.8	2.0	5.7 2.3	46.3	BOW	4-6	EASY			
6	6/23/78	MOGHE MARLIN	BULK CARRIER	IN	0.9 0.4	2.8 1.3	3.3 1.3	7.8 7.0	2.0	2.6	2.4	1.0	4.4 1.9	33.3	BOW	4-6	EASY			
7	6/24/78	MOGHE MARLIN	BULK CARRIER	OUT	0.9 0.4	1.5 0.4	3.5 1.8	7.7 8.1	3.4	2.4	2.5	1.4	3.4 1.8	35.9	BOW	2-4	EASY			
8	11/01/78	CHEVRON WASHINGTON	OIL CARRIER	IN	2.3 0.7	4.8 1.4	8.0 2.0	16.4 20.3	5.3	6.4	5.4	1.8	8.5 2.8	53.1	BOW	6-8	MODERATE			
9	11/04/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.7 0.8	6.2 2.3	6.6 2.7	11.6 13.9	5.9	10.1	9.7	3.6	7.3 2.7	40.9	BOW	4-6	EASY			
10	11/09/78	CHEVRON WASHINGTON	OIL CARRIER	IN	1.8 0.7	3.8 1.3	5.5 2.0	13.1 15.0	5.3	5.0	4.6	2.0	5.9 2.3	48.2	BOW	6-8	EASY			
11	11/10/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.2 0.5	2.1 0.7	4.5 2.2	9.3 10.6	4.4	3.6	3.1	2.0	4.3 2.2	33.1	BOW	6-8	EASY			
12	11/28/78	ALASKA MARU	CONTAINER CARRIER	IN	0.8 0.4	4.0 1.3	1.8 0.8	5.5 6.2	2.4	3.2	2.8	1.3	3.5 1.2	33.7	STERN	6-8	EASY			
13	12/03/78	CHEVRON COLORADO	OIL CARRIER	IN	0.8 0.4	2.3 0.8	2.9 1.3	6.6 6.9	2.4	2.7	2.7	1.0	3.9 1.5	40.3	BOW	6-8	EASY			
14	12/04/78	CHEVRON COLORADO	OIL CARRIER	OUT	2.9 1.2	13.4 3.7	8.4 3.1	22.6 22.0	8.5	12.1	12.1	4.5	10.1 3.2	46.3	BOW	2-4	MODERATE			
15	12/15/78	HILLVER BROWN	OIL CARRIER	IN	6.0 1.9	17.5 4.4	9.7 2.7	16.1 16.7	6.0	32.6	21.9	9.8	16.1 4.9	51.2	STERN	4-6	DIFFICULT			
16	12/17/78	HILLVER BROWN	OIL CARRIER	OUT	4.9 2.2	13.0 5.1	8.3 2.5	21.6 19.8	9.5	27.9	25.7	10.7	12.7 4.0	53.9	STERN	4-6	DIFFICULT			
17	12/29-30/78	ALASKA MARU	CONTAINER CARRIER	IN	0.7 0.3	2.3 0.8	2.5 0.8	4.6 4.2	1.5	2.7	2.4	1.1	3.0 1.0	32.5	BOW	4-6	EASY			
18	1/16/79	MAUNA LEI	CONTAINER CARRIER	IN	1.7 0.4	2.6 1.1	3.8 1.2	3.6 5.1	1.3	12.5	7.7	2.6	4.3 1.5	37.7	STERN	4-6	EASY			
19	1/19/79	MAUNA LEI	CONTAINER CARRIER	OUT	5.2 1.7	14.5 4.4	12.4 3.7	17.0 19.4	6.9	38.3	24.8	10.8	15.5 4.4	56.3	STERN	6-8	MODERATE			
20	1/21/79	HIKAWA MARU	CONTAINER CARRIER	IN	1.2 0.4	5.7 2.7	2.5 0.8	8.0 7.6	2.5	4.2	5.7	1.5	5.9 2.6	36.6	STERN	6-8	MODERATE			
21	1/24/79	GOLDEN ARROW	CONTAINER CARRIER	IN	1.8 0.8	11.7 5.1	4.0 1.6	12.0 12.3	4.4	6.8	7.4	2.7	10.4 3.8	41.1	STERN	6-8	MODERATE			
22	1/28/79	ALASKA MARU	CONTAINER CARRIER	IN	1.5 0.6	8.1 3.1	3.8 1.2	11.7 11.7	4.2	6.9	5.4	2.3	7.0 2.9	40.2	BOW	6-8	EASY			
23	2/07/79	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	1.1 0.4	5.6 1.7	2.3 0.9	9.0 8.1	2.9	3.2	4.5	1.7	6.0 1.8	40.7	BOW	4-6	MODERATE			
24	2/11/79	BEISHU MARU	CONTAINER CARRIER	IN	0.8 0.3	4.3 1.7	1.4 0.6	5.8 4.3	1.8	3.1	3.3	1.2	3.7 1.7	33.8	STERN	6-8	EASY			
25	2/22/79	GOLDEN ARROW	CONTAINER CARRIER	IN	0.9 0.4	6.0 2.7	1.8 0.7	5.9 4.4	2.1	2.4	3.0	1.3	5.1 2.1	37.6	STERN	2-4	EASY			
26	2/27/79	ALASKA MARU	CONTAINER CARRIER	IN	0.6 0.3	3.2 1.3	1.4 0.6	4.8 3.9	1.6	2.3	2.2	0.9	3.6 1.3	34.0	SIDE	8-10	EASY			
27	3/14/79	BEISHU MARU	CONTAINER CARRIER	IN	0.9 0.5	5.4 2.2	1.9 0.9	7.2 6.9	3.0	3.5	3.7	1.6	5.8 2.0	36.1	STERN	6-8	EASY			
28	3/22/79	CHEVRON WASHINGTON	OIL CARRIER	IN	1.6 0.6	3.6 1.4	6.1 1.8	14.6 12.0	4.3	5.6	4.5	1.9	7.1 2.3	38.3	BOW	6-8	EASY			
29	3/23/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.8 0.7	3.7 1.0	5.5 1.9	13.0 15.2	5.1	6.3	6.5	2.1	4.8 2.0	38.5	BOW	2-4	EASY			

* Data not available due to Mini-Ranger failure and no log to retrieve location in channel.

TABLE 7b
SUMMARY OF VERTICAL MODE MOTIONS
(PHASE II)

VOYAGE NO.	DATE	VESSEL		TRANSIT DIRECTION	VESSEL MOTIONS (Amplitude)						VERTICAL MOVEMENT AT VARIOUS PORTIONS OF SHIP								MAXIMUM VESSEL PENETRATION				PILOT'S RATING OF TRANSIT
		NAME	TYPE		PITCH (DEG)	ROLL (DEG)		HEAVE (FT)		BOW (FT)		STERN (FT)		SIDE (FT)	AMPLITUDE (FT)	PORTION OF SHIP	LOCATION IN CHANNEL (BETWEEN BUOYS)						
						MAX AGE	AVER-AGE	MAX AGE	AVER-AGE	MAX UP	MAX DOWN	MAX UP	MAX DOWN					MAX UP	MAX DOWN	MAX AGE	AVER-AGE		
30	10/16/79	CHEVRON ARIZONA	OIL CARRIER	IN	0.4	0.3	1.2	0.5	1.4	0.8	3.3	3.5	1.3	1.4	1.25	0.7	2.1	0.9	36.3	BOW	6-8	EASY	
31	10/17/79	CHEVRON ARIZONA	OIL CARRIER	OUT	2.8	1.5	8.6	2.8	9.7	4.1	23.3	22.9	11.2	12.0	9.1	4.4	7.9	3.1	44.8	BOW	4-6	EASY	
32	10/28/79	ALASKA MARU	CONTAINER CARRIER	IN	1.4	0.5	3.9	1.8	3.2	1.0	6.4	10.1	2.9	4.6	4.1	1.6	4.5	2.1	32.0	BOW	6-8	EASY	
33	11/14/79	HÖGCH MUSKETEER	BULK CARRIER	IN	0.4	0.15	1.5	0.47	1.5	.58	3.6	2.4	1.18	0.66	0.8	0.38	2.4	0.74	30.10	STERN	4-6	EASY	
34	11/17/79	HÖGCH MUSKETEER	BULK CARRIER	OUT	1.4	0.6	2.8	1.1	5.9	2.3	10.2	13.5	5.0	5.6	4.6	2.3	5.5	2.4	40.5	BOW	2-4	EASY	
35	11/21/79	MAUNA LEI	CONTAINER CARRIER	OUT	2.9	1.1	2.9	1.1	5.2	2.1	12.6	12.7	4.6	17.4	14.0	6.7	4.8	1.4	43.0	STERN	6-8	EASY	
36	11/26/79	GOLDEN ARROW	CONTAINER CARRIER	IN	0.7	0.3	5.6	1.9	2.4	0.9	5.7	4.7	1.7	3.0	3.1	1.2	4.7	1.7	37.4	SIDE	6-8	EASY	
37	11/28/79	HÖGCH MASCOT	BULK CARRIER	IN	0.6	0.3	1.5	0.4	2.3	0.7	5.3	3.9	1.2	1.1	1.0	0.5	1.1	0.5	26.5	STERN	2-4	EASY	
38	12/03/79	HÖGCH MASCOT	BULK CARRIER	OUT	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	MODERATE	
39	12/16/79	CHEVRON WASHINGTON	OIL CARRIER	IN	0.4	0.2	1.3	0.4	0.4	0.3	2.0	1.7	0.7	1.8	2.1	0.8	0.8	0.4	36.0	STERN	6-8	EASY	
40	12/18/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	2.1	1.0	2.0	0.8	6.0	2.8	15.2	15.8	7.9	7.4	7.5	3.2	5.7	2.6	37.3	BOW	2-4	EASY	
41	1/20/80	HIKAMA MARU	CONTAINER CARRIER	IN	0.5	0.2	2.4	1.2	0.9	0.5	3.6	4.1	1.0	2.2	1.8	0.7	2.2	1.2	32.4	BOW	6-8	EASY	
42	1/24/80	GOLDEN ARROW	CONTAINER CARRIER	IN	1.0	0.3	5.5	2.2	1.0	0.4	3.0	4.8	1.3	5.1	3.5	1.3	3.7	1.5	35.6	STERN	4-6	EASY	
43	2/04/80	WORLD WING	AUTO CARRIER	IN	1.0	0.4	2.7	1.0	2.0	0.7	2.5	3.6	1.6	5.9	4.3	1.6	2.4	1.0	28.6	STERN	4-6	EASY	
44	2/06/80	WORLD WING	AUTO CARRIER	OUT	3.0	1.0	3.2	1.1	6.2	2.6	15.0	16.6	9.5	8.0	8.6	3.2	8.6	3.2	38.9	BOW	6-8	MODERATE	
45	2/10/80	HÖGCH MUSKETEER	BULK CARRIER	IN	0.9	0.3	1.9	0.9	1.4	0.6	3.7	3.0	1.4	3.7	4.8	1.7	2.2	0.9	36.3	STERN	6-8	EASY	
46	2/14/80	HÖGCH MUSKETEER	BULK CARRIER	OUT	2.8	0.7	1.3	0.5	6.0	2.8	19.2	14.4	6.8	4.0	3.7	1.9	8.1	2.4	42.6	BOW	4-2	EASY	
47	3/04/80	MAUNA LEI	CONTAINER CARRIER	IN	1.1	0.4	5.6	1.6	1.9	0.7	5.5	6.3	2.0	5.5	3.6	1.5	2.9	0.9	31.8	BOW	6-8	EASY	
48	3/10/80	LIONS GATE BRIDGE	CONTAINER CARRIER	IN	1.7	0.5	5.0	2.0	3.3	0.9	12.9	9.6	2.9	5.7	5.9	1.8	5.2	1.8	40.0	BOW	6-8	EASY	
49	3/18/80	HÖGCH MERCHANT	BULK CARRIER	IN	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	EASY	
50	3/22/80	HÖGCH MERCHANT	BULK CARRIER	OUT	2.2	0.8	3.9	1.4	8.5	2.5	16.8	18.5	5.9	7.6	6.8	2.8	6.5	2.3	49.7	BOW	6-4	MODERATE	
51	3/26/80	GOLDEN ARROW	CONTAINER CARRIER	IN	1.6	0.5	13.3	5.5	3.6	0.9	10.2	9.0	2.4	6.0	6.1	2.0	11.4	4.0	44.2	SIDE	4-6	EASY	
52	4/01/80	ALASKA MARU	CONTAINER CARRIER	IN	2.4	0.7	7.1	2.6	5.8	1.4	15.7	18.1	3.8	8.7	8.2	2.2	6.9	2.0	49.8	BOW	4-6	MODERATE	
53	4/03/80	HÖGCH MALLARD	BULK CARRIER	IN	0.5	0.3	1.7	0.6	0.9	0.4	2.7	2.8	0.8	3.1	3.0	1.0	1.7	0.7	33.1	STERN	6-8	EASY	

Δ No data due to equipment failure

the data presented in Table 1, this information is listed according to the order of the voyage number. Oscillatory motions of pitch, roll and heave are presented in the table. In addition, vertical excursions at various locations of interest, namely the bow, the stern and the extreme beam side of the ship are determined and given in the table. All motions are presented in amplitude relative to the mean line. Two values for each motion parameter were processed from the measurements and are presented in the table; they are the maximum and the average. The maximum value is the largest amplitude in the data segment being processed, and the average value is the arithmetic mean of all the peak amplitudes in the same data segment. In order to show the effect of ship motion on the bottom clearance, the downward and upward excursions of the bow and stern motions are separately presented. The vertical excursion on the portside, in general, is not equal to that on the starboard side due to the phase shift between heave and roll. Since this parameter is not considered as critical as the bow and stern motions for a regular shape vessel, only the maximum motions on the portsides (upward or downward) are presented.

The motions of bow, stern and side of these ships provide the fundamental information for analysis of the channel depth requirement. By considering the loading condition of each vessel at transit, the maximum vertical vessel penetration over the whole entrance channel on each voyage is also determined and presented in the table. The maximum penetration is defined as the maximum total immersion of a ship; it is determined by summing up the maximum downward excursion with the local draft. The difference of this value from the channel depth indicates the minimum bottom clearance in a particular voyage. It is clear that this maximum immersion or the minimum clearance may occur at the bow, the stern, or the bilge keel of a ship.

Table 7 includes also the information on channel location where the maximum motion or penetration occurred during each voyage. This information is presented in terms of the location of the buoys outside the entrance channel. The distance between any two neighboring buoys is approximately one nautical mile. From this information, the critical water depth along the channel can be examined, should a variable depth channel be considered. For the same purpose, the variations of the motion excursion along the whole channel length are detailed in Table 8.

For those readers who are interested in the basic motion data, the time history, the vessel track, and the cumulative frequency plots for the entire 53 voyages are included and given in Appendix A.

7.2 VESSEL PENETRATION AND CHANNEL CLEARANCE

As part of the data acquisition for each voyage a copy of the ship's fathometer record, during the transit through the entrance channel, was made. It was hoped that these records could be used to correlate and substantiate the computed vertical vessel motions as the fathometer is intended to provide a measure of the depth of water below keel. Although the fathometer record is not truly a measure of the vertical vessel motions, several interesting observations and comparisons can be made with the computed vertical vessel motions and the ship's trajectory plot through the channel.

Voyage No. 52 is an interesting case for consideration. The ship trajectory plot is shown in Figure 14. The corresponding fathometer and computed heave records are shown in Figure 15. The fathometer record is compared to the heave record for this voyage because the fathometer transducer was located near mid-ship and therefore most nearly resembles the heave record. The location of the ship relative to the channel buoys is readily discernible from the ship trajectory plot and these

TABLE 8a
MAXIMUM SHIP MOTIONS AT VARIOUS CHANNEL LOCATIONS
(PHASE I)

VOYAGE NO.	PITCH, DEG.				HEAVE, FT.				ROLL, DEG.				TOTAL VESSEL PENETRATION*, FT.			
	LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY			
	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10
1	1.3	2.2	2.5	1.4	3.7	6.7	7.0	4.3	3.2	5.3	6.4	3.1	41.3	47.3	<u>49.5</u>	44.9
2	1.3	1.0	1.1	0.4	3.5	3.6	3.3	1.2	1.7	2.9	2.2	1.0	<u>43.8</u>	41.7	41.3	35.3**
3																
4	2.0	0.8	0.7	0.7	4.2	3.4	2.7	2.8	0.8	0.9	1.3	1.3	<u>31.3</u>	29.6*	29.6*	29.2*
5	1.0	1.5	1.4	1.2	3.6	4.7	4.7	4.2	2.4	3.5	3.8	2.1	43.0	<u>46.3</u>	45.0	43.5
6	0.6	0.9	0.7	0.3	2.1	3.3	3.0	1.3	2.4	2.5	2.8	2.1	31.3	<u>33.3</u>	32.3	30.3**
7	0.9	0.7	0.8	0.9	3.4	3.2	3.3	3.5	1.2	1.0	1.5	0.9	35.7	34.6	34.2	<u>35.9</u>
8	1.3	1.6	2.3	1.2	4.5	6.2	8.0	4.6	2.3	3.0	3.1	3.3	43.2	44.2	<u>53.1</u>	43.6
9	1.2	1.7	1.7	0.9	4.7	6.0	6.6	3.1	2.7	5.4	6.2	1.2	37.2	<u>40.9</u>	39.7*	34.8
10	1.3	1.6	1.8	0.7	5.6	4.8	5.5	3.0	2.0	3.8	2.7	1.6	43.1	46.4	<u>48.2</u>	40.2
11	0.8	1.1	1.2	0.8	3.6	3.7	4.5	2.9	1.0	1.4	2.1	0.9	29.9	31.3	<u>33.1</u>	29.7
12	0.8	0.6	0.8	0.6	1.7	1.5	1.8	1.0	2.3	3.4	3.4	4.0	32.9*	33.2*	<u>33.7*</u>	32.7*
13	0.7	0.6	0.8	0.3	2.4	2.2	2.9	1.1	1.7	1.5	2.3	1.9	39.6	39.7	<u>40.3</u>	36.2
14	2.9	2.6	2.7	1.4	8.3	8.4	8.3	4.5	5.4	7.4	13.4	1.8	<u>46.3</u>	40.0	38.1	31.9
15	6.0	4.6	5.3	1.8	7.9	6.5	9.7	2.3	12.3	17.4	10.3	3.5	51.0*	<u>51.2*</u>	48.0*	34.3*
16	5.0	4.9	4.8	3.5	4.7	8.3	5.8	3.7	9.7	13.0	10.0	1.2	48.7*	<u>53.2*</u>	50.7*	43.4*
17	0.4	0.6	0.7	0.7	1.6	1.9	2.5	1.9	2.5	1.9	2.3	1.8	31.8	<u>32.5</u>	32.1	31.7
18	0.8	1.7	1.0	0.4	3.0	3.8	2.3	1.5	1.5	1.8	2.6	1.5	36.9*	<u>37.7*</u>	<u>37.7*</u>	33.5*
19	2.2	5.2	3.4	2.8	6.0	8.3	12.4	5.0	6.0	8.7	14.5	2.7	49.0*	54.0*	<u>55.2*</u>	46.0*
20	3.6	0.8	1.2	0.4	1.3	1.9	2.5	0.7	3.8	5.3	5.8	4.0	33.3*	34.3**	<u>36.5*</u>	32.8**
21	1.6	1.5	1.8	1.2	3.2	3.8	4.0	2.6	7.7	11.0	11.7	3.9	38.4*	38.7**	<u>41.2*</u>	37.8*
22	1.4	1.4	1.5	0.5	2.3	3.6	3.3	2.4	5.5	8.2	7.2	3.7	39.3	39.5	<u>40.2</u>	33.1
23	1.1	1.1	0.8	0.5	2.2	2.3	2.1	1.2	4.8	5.6	4.4	3.4	40.1	<u>40.7</u>	38.2	36.1
24	0.8	0.6	0.7	0.3	1.2	1.4	1.4	0.8	2.5	4.3	3.6	3.2	33.7*	32.7*	<u>33.3**</u>	32.4**
25	0.9	0.6	0.7	0.7	1.4	1.2	1.8	1.6	5.6	3.0	6.1	4.3	<u>37.7*</u>	37 *	37.1*	36.5*
26	0.4	0.5	0.4	0.6	1.0	1.4	1.2	1.4	2.6	2.8	2.9	3.2	33.4	33.4	33.2	<u>34.0**</u>
27	0.6	0.8	0.9	0.6	1.3	1.6	1.9	1.4	3.1	3.7	5.4	3.2	34.9*	35.8*	<u>36.1*</u>	34.9*
28	1.3	1.6	1.5	0.7	4.3	4.9	6.1	2.6	2.1	3.5	3.6	1.4	37.1	38.1	<u>39.3</u>	32.5
29	1.8	1.6	1.7	1.0	5.5	4.9	4.9	3.4	3.7	1.9	2.0	0.8	<u>39.5</u>	37.1	36.2	32.3

* Vessel penetration refers to the bow unless otherwise indicated

* Stern

** Side

Numbers with underline indicate the maximum penetration over the channel

† Data not available due to Mini-Ranger failure and no log to retrieve location in channel

TABLE 8b
MAXIMUM SHIP MOTIONS AT VARIOUS CHANNEL LOCATIONS
(PHASE II)

VOYAGE NO.	PITCH, DEG.				HEAVE, FT.				ROLL, DEG.				TOTAL VESSEL PENETRATION, FT.			
	LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY				LOCATION IN CHANNEL, BUOY TO BUOY			
	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10	2-4	4-6	6-8	8-10
30	0.4	0.4	0.4	0.3	1.4	1.4	1.4	1.4	1.05	0.8	1.1	1.2	36.1	36.2	<u>36.4</u>	35.8
31	2.7	2.7	2.8	2.5	7.8	9.1	9.7	7.0	6.0	4.6	8.4	2.8	42.9	<u>44.8</u>	42.9	42.4
32	0.3	0.9	1.4	0.8	1.9	2.3	2.6	2.2	3.6	3.7	3.9	4.5	36.9	37.7	<u>41.00</u>	37.10
33	0.2	0.4	0.2	0.2	1.0	1.5	1.4	0.8	0.9	1.5	1.0	0.8	29.8*	<u>30.1*</u>	30.0 *	29.3 *
34	1.4	1.3	1.4	0.95	5.9	5.5	5.1	4.3	1.3	3.0	2.7	1.0	<u>40.5</u>	38.0	38.6	36.5
35	2.1	2.0	2.9	1.8	4.9	4.4	5.2	3.2	2.8	2.0	2.9	2.2	<u>41.2*</u>	42.0*	<u>43.0 *</u>	37.0 *
36	0.6	0.6	0.7	0.3	1.8	1.8	2.4	2.6	4.6	4.4	5.6	5.8	36.6*	36.4*	37.3 *	<u>37.7 **</u>
37	0.6	0.4	0.4	0.6	2.3	1.65	1.6	2.1	0.8	0.6	1.5	1.7	26.5*	26.4*	26.2 *	<u>26.90*</u>
138																
39	0.3	0.2	0.4	0.2	0.37	0.35	0.44	0.43	1.4	0.8	1.3	1.2	35.6*	35.4*	<u>36.0 *</u>	35.3 *
40	2.1	2.1	1.9	1.6	5.5	5.4	6.0	5.0	1.3	2.0	1.9	1.4	<u>37.3</u>	36.3	36.9	33.9
41	0.2	0.2	0.5	0.2	0.6	0.9	1.0	0.8	2.0	2.4	2.3	2.3	32.0	32.3*	<u>32.7 *</u>	32.0 *
42	0.4	0.5	1.0	0.2	0.8	0.8	1.0	0.5	5.5	3.5	4.4	4.6	34.2*	<u>35.6*</u>	34.8 *	33.4 *
43	0.6	1.0	0.8	0.8	1.5	1.9	1.9	1.1	2.3	2.8	2.7	2.6	28.5*	<u>28.6*</u>	27.6 *	27.6 *
44	2.9	3.0	3.0	2.3	5.5	6.2	5.8	5.9	1.2	2.9	3.2	2.0	27.8	38.3	<u>38.8</u>	32.3
45	0.7	0.6	0.8	0.8	1.3	1.5	1.1	0.9	1.5	1.6	1.9	1.7	35.1*	35.2*	<u>36.3 *</u>	34.5 *
46	2.6	1.5	1.6	1.2	5.5	6.5	6.0	4.0	0.7	1.3	1.3	1.3	40.0	42.6	42.5	38.2
47	0.7	0.7	1.1	0.4	1.3	1.3	1.9	0.6	2.0	2.2	5.6	2.8	29.1	29.2	<u>31.3</u>	28.2
48	1.2	6.9	1.7	2.0	2.2	1.9	3.3	3.3	3.9	4.5	5.0	3.4	38.4	37.6	<u>39.6</u>	39.0 *
149																
50	2.1	2.2	1.9	1.0	7.3	8.5	5.5	4.7	3.4	3.9	3.6	0.9	48.3	<u>49.2</u>	44.9	41.5
51	1.2	1.6	1.2	1.1	2.1	3.6	2.1	1.9	10.0	13.0	10.5	9.0	39.5*	<u>40.4**</u>	37.8 *	37.6 *
52	1.2	2.4	1.6	1.6	3.6	5.9	3.8	3.0	3.8	6.2	7.1	6.0	41.0	<u>49.3</u>	42.8	39.6 *
53	0.4	0.5	0.5	0.6	0.34	0.66	0.9	0.78	1.2	1.7	1.7	1.3	32.2*	33.0*	32.9 *	<u>33.9 *</u>

* Vessel penetration refers to the bow unless otherwise indicated

* Stern

** Side

Numbers with underline indicate the maximum penetration over the channel

* No data due to equipment failure

VUYGHE MD. K2 SHIP TRACK SCALE 1: 30000

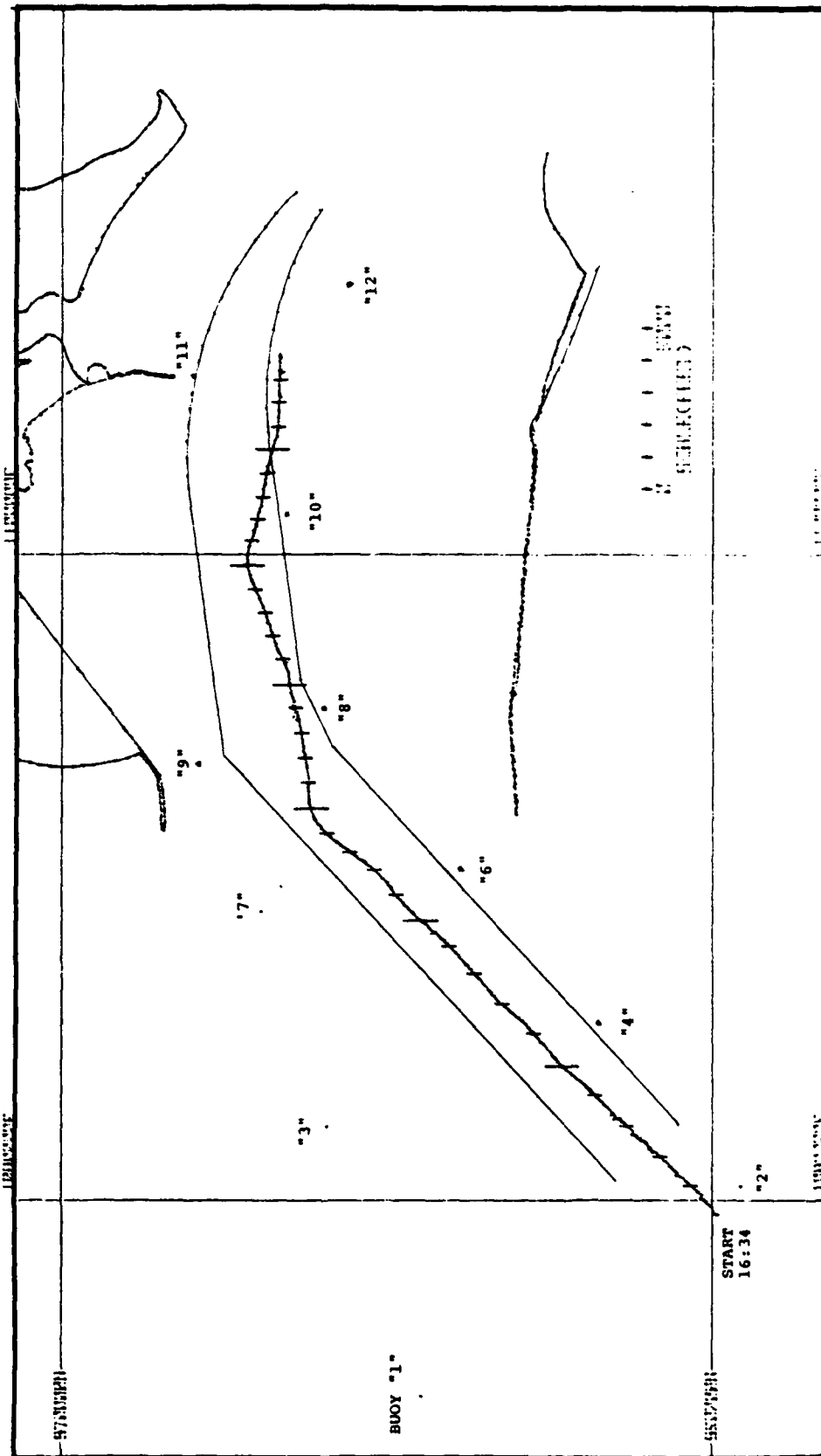


FIGURE 14 SHIP TRAJECTORY PLOT FOR VOYAGE NO. 52

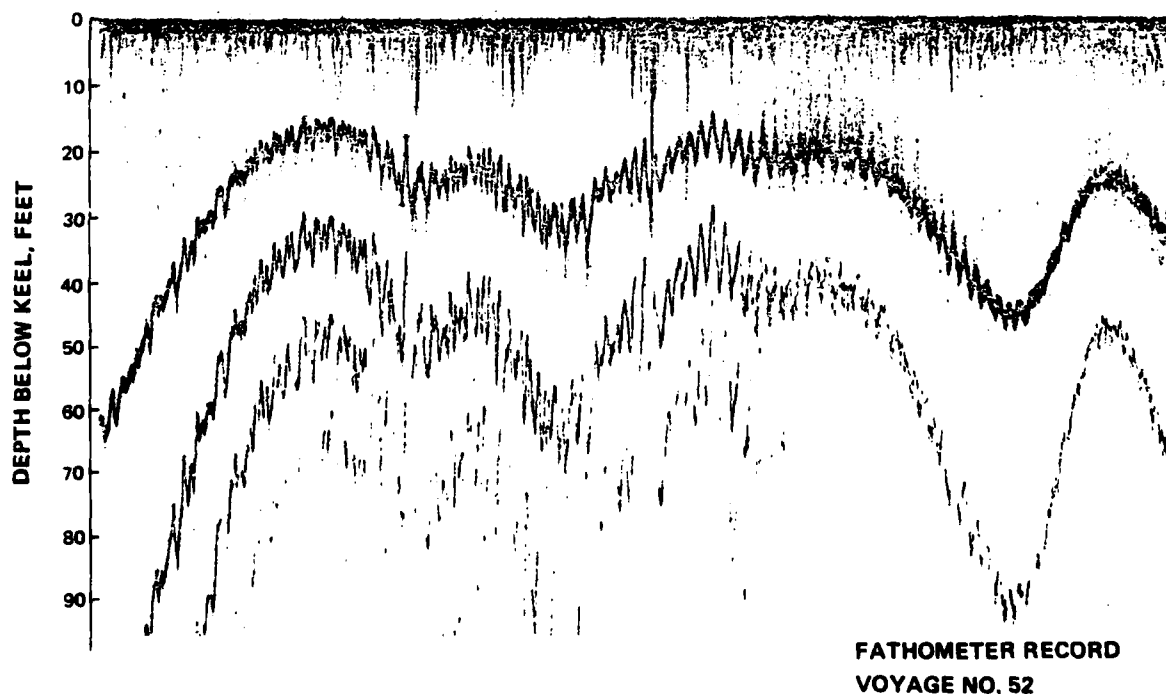
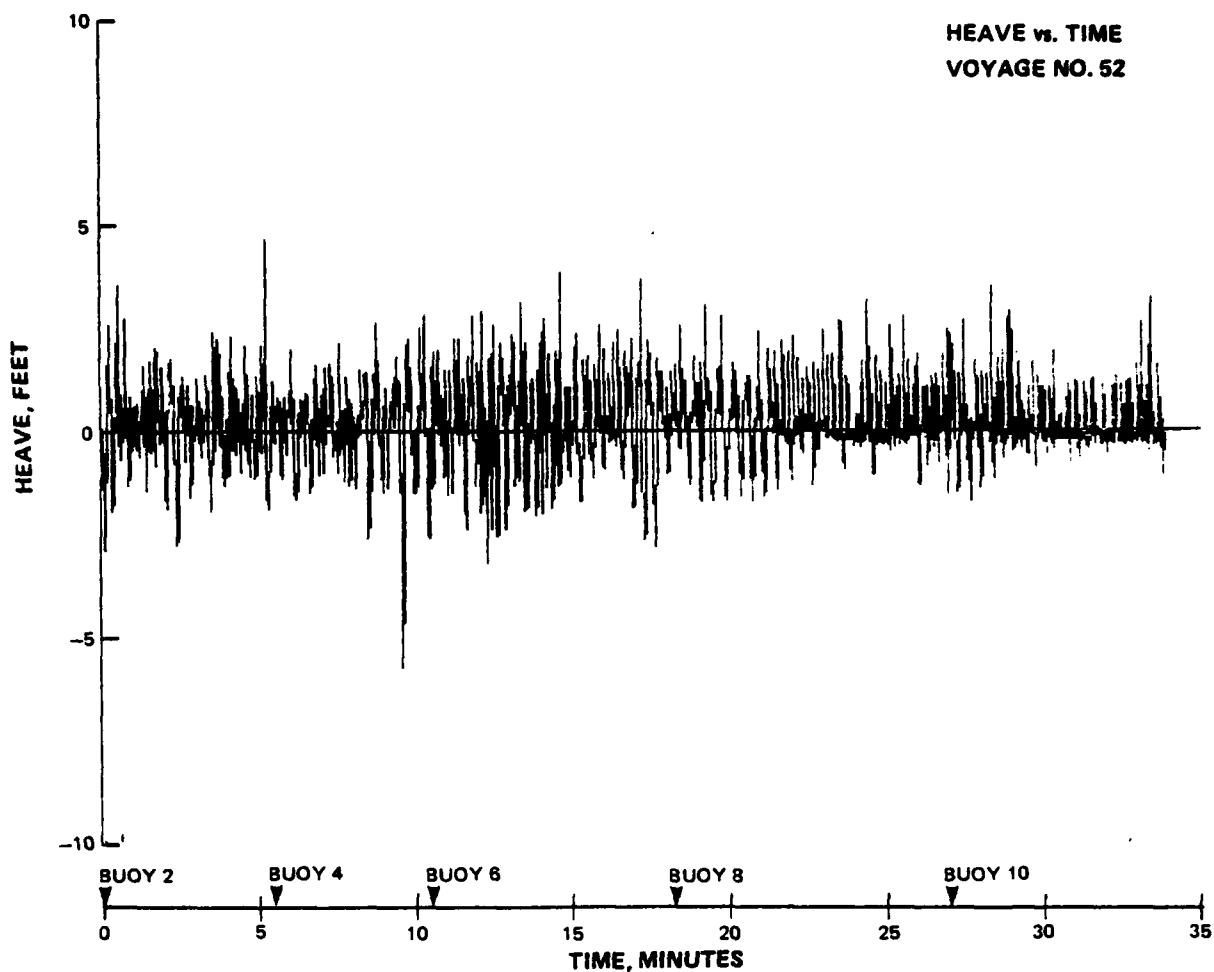


FIGURE 15 - FATHOMETER AND HEAVE RECORDS FOR VOYAGE NO. 52

locations have been superimposed on the fathometer and heave records for reference. The ship trajectory plot with the fathometer and heave records combine to form a three dimensional plot of the ship track relative to the confines of the channel.

Based upon the computed vessel motions the maximum penetration of 49.8 ft, at the bow, occurred approximately 9.5 minutes into the voyage between buoy Nos. 4 and 6. The maximum penetration is clearly evident in both the fathometer and heave records. In comparison to the Army Corps of Engineers project depth of 48 ft for the Columbia River Entrance Channel, it appears that the ship would have bottomed out. However, by correlating the position of the ship in the channel at the time of maximum penetration with a hydrographic survey made near the time of the voyage, it was determined that the water depth was actually around 54 ft. Additionally, the tidal stage at the time of the crossing was + 3 ft, making the total water depth approximately 57 ft. Assuming a water depth of 57 ft and a penetration of 49.8 ft, the vessel still had a clearance of 7.2 ft.

Based on the fathometer record the clearance under keel at the time of maximum penetration was around 18 ft. This is not in contradiction with the clearance as determined above. The first represents the clearance at the extreme bow while the second represents the clearance near midships. The maximum penetration based on the computed heave record is 5.8 ft of heave plus 32.6 ft of draft for a total penetration of 38.4 ft. Near midships with a water depth of 57 ft, this translates to a midship clearance of 18.6 ft which is in good agreement with that obtained from the fathometer record.

It is also interesting to look at the bottom profile shown on the fathometer record. At buoy No. 2 the bottom has already begun to rise sharply and continues to do so till a peak is reached near buoy No. 4. The Columbia River bar can clearly be seen between buoy Nos. 4 and 6. Typically, this is the region where wave conditions are most severe as they tend to break on the bar, especially when in conjunction with an ebb current.

A similar analysis has been carried out for those voyages where the maximum penetration exceeded the Army Corps of Engineers project depth of 48 ft. Results of the analysis are presented in Table 9. Comparisons of the calculated with the recorded under keel clearances show fairly good agreement for most of the voyages. Finally, the location of maximum vessel penetration for each of these voyages has been superimposed on the channel outline as shown in Figure 16.

7.3 CORRELATION WITH CHARACTERISTIC VARIABLES

Five variables are considered relevant to the study of vessel motions in the entrance channel: 1) ship characteristics, 2) wave conditions, 3) transit direction, 4) ship speed, and 5) tide. Some general remarks concerning the effect of these variables on the resulting motions can be summarized as follows:

- 1) Effect of Ship Characteristics. As discussed in Section 4.2, there were altogether 18 ships that participated in the present phase of the program and these 18 ships are categorized into four groups: tankers, containerships, bulk carriers, and one auto carrier. The characteristics of these ships, as shown in Table 2, are different among groups or even within a group. Nevertheless, these ships fall approximately into one length class.

Observations and results of measurements from the present program indicate that the tankers appear to pitch slightly more than the bulk carriers and containerships. Only one auto carrier was monitored in this measurement program. This ship is a relatively smaller one compared to others. Characteristically, it very much resembles the containerships. The containerships have finer lines at bow and stern and are definitely superior in terms of seakeeping qualities. On the other hand, the tankers are the fullest among the three groups of ships, and theoretically should have a higher pitch response at least in the range of wave

TABLE 9
COMPARISON OF MAXIMUM VESSEL PENETRATION WITH FATHOMETER RECORD

VOYAGE NUMBER	MAXIMUM VESSEL PENETRATION (ft)	WATER [†] DEPTH (ft)	TIDAL STAGE AT TIME OF VOYAGE (ft)	TOTAL WATER DEPTH AT TIME OF VOYAGE (ft)	MINIMUM UNDER KEEL CLEARANCE (ft)	LOCATION OF FATHOMETER TRANSDUCER	UNDER KEEL CLEARANCE AT FATHOMETER TRANSDUCER	
							BASED ON FATHOMETER RECORD (ft)	BASED ON COMPUTED VERTICAL VESSEL MOTIONS (ft)
1	49.5 @ bow	52	+ 3.5-flood	55.5	6.0	bow	18	6.0
8	53.1 @ bow	53a	+ 6.2-ebb	59.2	6.1	bow	11	6.1
10	48.2 @ bow	52	+ 3.9-flood	55.9	7.7	bow	14.5	7.7
15	51.2 @ stern	53	+ 3.5-ebb	56.5	5.3	midships	c	23.1
16	53.9 @ stern	51	+ 7.5-slack	58.5	4.6	midships	20	23.5
19	56.3 @ stern	57	+ 4.9-ebb	61.9	5.6	near bow	24	24.9
50	49.2 @ bow	54/49b	+ 2.2-flood	56.2/51.2	7.0/2.0	bow	8.0/10.0	7.0/2.0
52	49.8 @ bow	54	+ 3.0-ebb	57.0	7.2	midships	18	18.6

[†] As determined by correlating time of maximum vessel penetration, ship trajectory plot, and the Condition Survey of Columbia River Mouth by the Portland District, Corps of Engineers that most nearly corresponded to the date of the voyage. Depth relative to MLLW.

a) No ship trajectory plot available. Water depth estimated.

b) Maximum vessel penetration occurred in two areas of the channel.

c) Unable to determine under keel clearance from fathometer record.

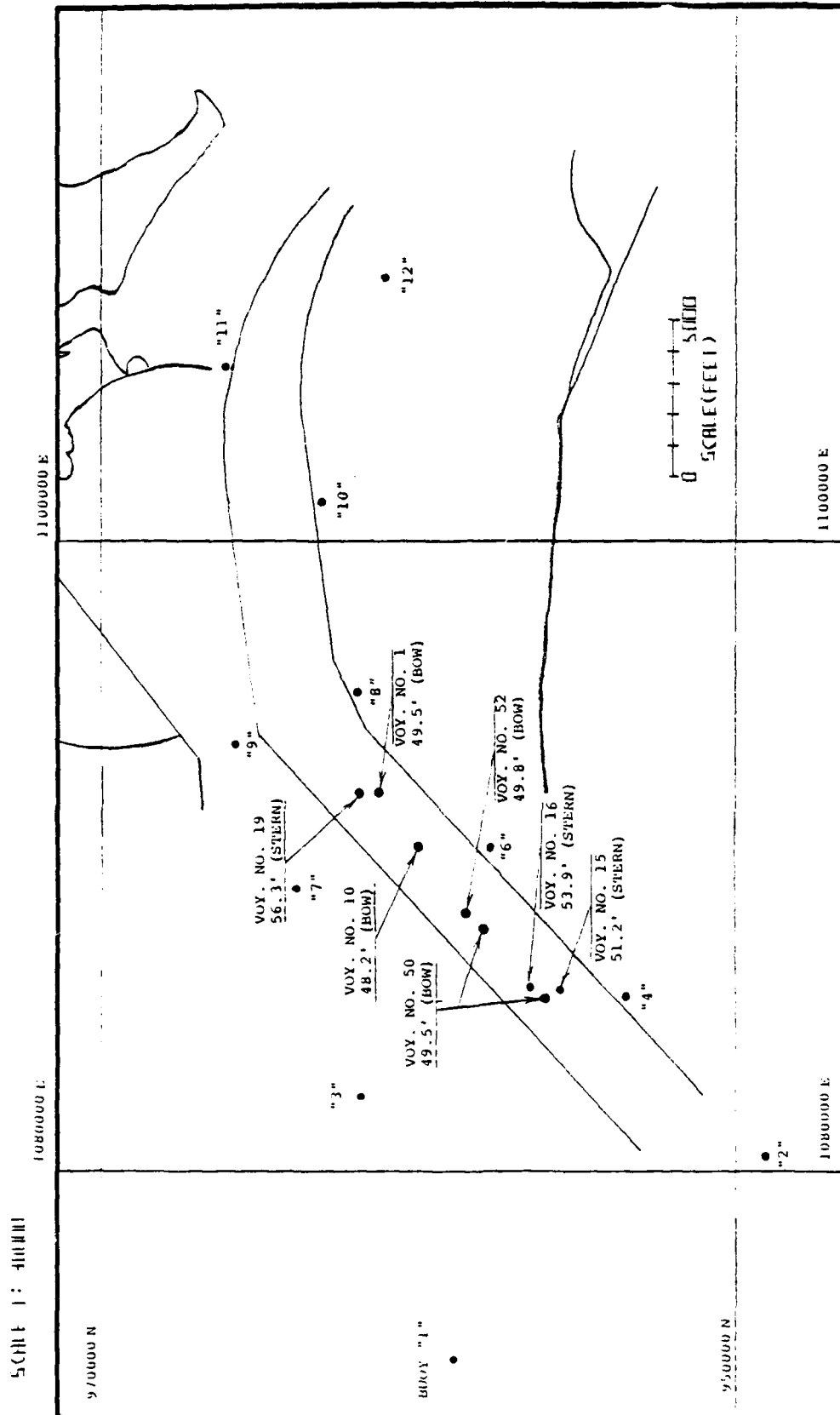


FIGURE 16 - LOCATIONS OF MAXIMUM VESSEL PENETRATIONS

lengths encountered. In terms of vertical motions, therefore, the containerships seem to exhibit the smallest response, the bulk carriers an intermediate response, and the tankers the most pronounced response; the differences, however, are small.

As to roll, observations indicate that the bulk carriers and the auto carrier *World Wing* tend to roll more than others. However, the sea conditions were generally calm when their transits were recorded; significant correlations between roll and ship characteristics are not apparent in the data collected.

- 2) Effect of Wave Conditions. Both sea and swell were recorded from visual observations, and the data have been presented in Table 1. From these records, it is clear that swell was the dominant source of excitation responsible for vessel motions. Ship response is generally a function of wave period and height. From Table 1 it is seen that the variation in period in the 53 recordings is minor, with a predominant range between 8 and 10 seconds. If the period variation can be considered negligible, all motions should be proportional to wave height according to linear, small motion theory.

Observed wave heights range from 2 to 20 ft, as shown in Table 1. For waves of these heights with an average period of 9 seconds, the linear theoretical concept of ship motion can be applied with no serious violations. Consequently, motion variables normalized by wave amplitudes have been analyzed and will be discussed later.

- 3) Effect of Transit Direction. The Columbia River Entrance Channel has a northeast-southwest orientation. More precisely, the ideal inbound course in the channel would be 045° and the outbound would be 225° . In Table 1, one may find that the directions of swell recorded in the 53 voy-

ages are generally in the sector between northwest and west. This also agrees with the long term swell statistics discussed in Section 5. Consequently, the vessels typically experienced quartering seas from the port stern for inbound voyages and from the starboard bow for outbound voyages.

There is little difference in roll response for quartering bow seas or quartering stern seas, but the differences in pitch are sometimes significant. For a quartering bow sea, the ship is running into the waves. Since the relative velocity between the waves and the ship is higher than the actual wave velocity, the period which the ship feels is shorter than the wave period. On the other hand, a ship in a quartering stern sea would feel a longer apparent period. This period which the ship actually feels is called the period of encounter.

The average period of swell is approximately 9 seconds, as discussed earlier. The wave length is, therefore, on the order of the length of the vessels or slightly shorter. Over this range of wave length/ship length ratios, heave motions are generally small, but pitch motions are normally critical and sensitive to the ship encounter period or frequency. In general, ships heading into waves (shorter encounter period or higher encounter frequency) would have higher responses than following waves. Consequently, for the present case, it should be anticipated that the outbound voyages have higher vertical motion responses than the inbound voyages. The encounter periods calculated with respect to the observed wave periods are summarized in Appendix I.

For those occasions when a northwesterly swell prevails, there should be little significant difference in motion responses between inbound or outbound voyages, as in either transit direction a ship would experience a beam sea. Under a beam sea condition, the roll motion may become relatively more important, however. This is indeed shown in data of Voyage Nos. 1, 6, 8, 11, 30, 42, 47, 50, 51, and 52.

- 4) Effect of Ship Speed. As shown in Table 3, over the 53 voyages, the average speed is approximately 12 knots for the tankers, 16 knots for the containerships, and 14 knots for the bulk carriers. Variations from these average values are at least partly due to the channel wave and tide conditions.

Pitch and heave damping normally decreases as the ship speed increases. It is common practice for a captain to reduce speed in rough seas so as to minimize ship motions. In the present case, it is anticipated that the pilot would always order the ships at a normal cruising speed when the channel conditions and the ship responses permit doing so safely. Consequently the variation in speed is governed by wave, tide, and motions, and the effect of speed changes among those transits is not considered as an independent variable.

- 5) Effect of Tide. As pointed out before, the predominant wave condition at the entrance channel is a northwesterly through westerly swell. For swells of this direction, an ebb tide tends to steepen the wave front and sometimes even causes it to break if the oncoming swell is sufficiently high. A strong flood tide certainly could cause some steering problems for inbound vessels but the flood tide effect on waves generally brings about favorable consequences, at least in terms of vessel responses, as flood tide currents lengthen a west-northwesterly swell in the entrance channel and reduce the chance of breaking.

Short, steep and breaking waves are the major concerns in channel crossings and hopefully can be avoided. Consequently, a flood tide seems always a favorable choice over an ebb tide irrespective of transit direction. Nevertheless, the adverse effect of an ebb tide arises only when the oncoming swell is significant. Observations during the present program indicate that the direction of tidal currents is

inconsequential when swells are less than 10 ft (significant height).

It might be well to summarize here that among the five variables, the first three, ship characteristics, wave conditions and transit direction, primarily govern the vessel motions for the transit over the Columbia River Entrance Channel. Variations in ship speed are, in most cases, consequences of adverse sea conditions and, therefore, not considered independent. The effects of tides are generally not significant unless the sea is rough.

In order to examine the effects of these variables, measured data on pitch and vertical motions are analyzed. Assuming the linear procedure valid, motion variables normalized by the encounter wave amplitude are considered as a fundamental basis for comparison and analysis. Table 10 shows the normalized pitch and vertical motions for the 53 recorded transits. The vertical motion here implies the vertical excursion at the bow or stern, whichever is larger. For both pitch and vertical motions, the average values over each transit are considered as the basis of comparison. The wave amplitudes are taken as one-half of the observed wave heights. Although the observed heights do not correspond to the average heights statistically, this normalization does help to remove the effect of wave variations, and thus the normalized variables can be compared on the basis of equal wave conditions. The normalized vertical motion is a dimensionless quantity. This dimensionless variable is commonly termed a response amplitude ratio, signifying the ratio between the vessel response and the exciting waves. Similarly, the normalized pitch can be a dimensionless quantity if the amplitude of pitch is normalized by the wave slope, as normally adopted by naval hydrodynamicists. In the present case, however, since the variations in wave period are not considered significant, a simple normalization by wave amplitude is used for the angular pitch motion as well as for the vertical linear motions.

TABLE 10a
VESSEL RESPONSE AMPLITUDE RATIO
(PHASE I)

VOYAGE NUMBER	VESSEL	OBSERVED WAVE AMP (FT)	AVERAGE PITCH AMP (DEG)	RAT.O PITCH AMP/ WAVE AMP (DEG/FT)	AVERAGE* VERTICAL EXCURSION (FT)	RATIO VERTICAL EXCURSION/ WAVE AMP
1	Chevron Louisiana	3-4	0.9	0.26	7.3	2.09
2	Chevron Louisiana	3	0.6	0.20	4.2	1.40
3	Höegh Mallard	2	0.3	0.15	2.6	1.30
4	Höegh Mallard	2	0.4	0.20	2.8	1.40
5	Chevron Oregon	4-5	0.7	0.16	4.6	1.02
6	Höegh Marlin	2-3	0.4	0.16	2.0	0.80
7	Höegh Marlin	1-2	0.4	0.27	3.4	2.27
8	Chevron Washington	5	0.7	0.14	5.3	1.06
9	Chevron Washington	5-6	0.8	0.15	5.9	1.07
10	Chevron Washington	3	0.7	0.23	5.3	1.77
11	Chevron Washington	2.5	0.5	0.20	4.4	1.76
12	Alaska Maru	3	0.4	0.13	2.4	0.80
13	Chevron Colorado	1.5	0.4	0.27	2.4	1.60
14	Chevron Colorado	4-5	1.2	0.27	8.5	1.89
15	Hillyer Brown	7.5-10	1.9	0.22	9.8	1.12
16	Hillyer Brown	6-9	2.2	0.29	10.7	1.43
17 ^Δ	Alaska Maru	—	0.3	—	1.5	—
18	Mauna Lei	2-3	0.4	0.16	2.6	1.04
19	Mauna Lei	7.5-9	1.7	0.21	10.8	1.23
20	Hikawa Maru	5-6	0.4	0.07	2.5	0.45
21	Golden Arrow	5	0.8	0.16	4.4	0.88
22	Alaska Maru	5-6	0.6	0.11	4.2	0.76
23	Lion's Gate Bridge	5	0.4	0.08	2.9	0.58
24	Beishu Maru	3	0.3	0.10	1.8	0.60
25	Golden Arrow	1.5-2	0.4	0.23	2.1	1.20
26	Alaska Maru	3-4	0.3	0.09	1.6	0.46
27	Beishu Maru	2-3	0.5	0.20	3.0	1.20
28	Chevron Washington	3	0.6	0.20	4.3	1.43
29	Chevron Washington	2-3	0.7	0.28	5.1	2.04

* Bow or stern excursion, whichever is larger

^Δ No valid wave observations available

TABLE 10b
VESSEL RESPONSE AMPLITUDE RATIO
(PHASE II)

VOYAGE NUMBER	VESSEL	OBSERVED WAVE AMP (FT)	AVERAGE PITCH AMP (DEG)	RATIO PITCH AMP/ WAVE AMP (DEG/FT)	AVERAGE* VERTICAL EXCURSION (FT)	RATIO VERTICAL EXCURSION/ WAVE AMP
30	Chevron Arizona	2.5	0.3	0.12	1.3	0.52
31	Chevron Arizona	4-5	1.5	0.33	11.2	2.49
32	Alaska Maru	3-4	.5	0.14	2.9	0.83
33	Höegh Musketeer	1-2	0.2	0.13	0.4	0.25
34	Höegh Musketeer	3	0.6	0.20	5.0	1.67
35	Mauna Lei	3-4	1.1	0.31	4.6	1.31
36	Golden Arrow	1.5-3	0.3	0.08	5.7	1.43
37	Höegh Mascot	3-4	0.3	0.09	1.2	0.34
38Δ	Höegh Mascot	3-5	--	--	--	--
39	Chevron Washington	2-3	0.2	0.08	2.1	0.84
40	Chevron Washington	4	1.0	0.25	7.9	1.98
41	Hikawa Maru	2-3	0.2	0.08	1.0	0.40
42	Golden Arrow	3-4	0.3	0.09	1.3	0.37
43	World Wing	3-4	0.4	0.11	1.6	0.46
44	World Wing	5-8	1.0	0.15	9.5	1.46
45	Höegh Musketeer	2-3	0.3	0.12	1.7	0.68
46	Höegh Musketeer	2-3	0.7	0.28	6.8	2.72
47	Mauna Lei	3-4	0.4	0.11	2.0	0.57
48	Lions Gate Bridge	**	0.5	0.14	2.9	0.83
49Δ	Höegh Merchant	2-3	--	--	--	--
50	Höegh Merchant	4-5	0.8	0.18	5.9	1.31
51	Golden Arrow	3-4	0.5	0.14	2.4	0.69
52	Alaska Maru	4-5	0.7	0.16	3.8	0.84
53	Höegh Mallard	1-2	0.3	0.20	1.0	0.67

* Bow or stern excursion, whichever is larger

** The observed wave amplitude was 1-2 ft as shown in the voyage log. This data is suspectably wrong as compared to the measured wave data given in Section 9.2.

Δ A 3.5 ft wave amplitude is actually used in normalizing the motion amplitudes.

Δ No data due to equipment failure

Figure 17a shows for the 29 voyages of Phase I the variations of pitch and vertical motions in terms of the normalized parameters or the response amplitude ratios. Each individual data point is identified with the vessel monitored in the transit, the transit direction, and the tidal stage. These plots show a definite indication that the outbound voyages have higher motion responses than the inbound voyages. These results seem to agree well with the anticipated results discussed in the foregoing. The plots also tend to indicate that the container ships are the most seaworthy ships as compared to the tankers and bulk carriers. No clear indication of tidal effects on vessel motions can be drawn from the correlation, however. This is primarily due to the fact that wave conditions were too low to make tide effects significant in most cases, as discussed earlier. Figure 17b shows the same normalized parameters for the Phase II voyages. The results further substantiate the conclusions made in the Phase I study.

7.4 STATISTICAL DISTRIBUTIONS

As discussed in Section 6, time history data for each recording has been processed to obtain the cumulative frequency diagrams. These diagrams provide an immediate estimate of the probability of responses exceeding a given value. For example, the cumulative frequency diagrams for pitch, roll, heave and bow excursions for Voyage No. 9 have been shown in Figure 13, and under the particular sea conditions encountered in Voyage No. 9, the probability of the pitch amplitude of that particular ship (*Chevron Washington*) exceeding one degree is shown to be 42%.

As was also discussed in Section 6, on the basis of experimental evidence [7], the distribution of vessel responses can be approximated by the Rayleigh distribution if the environmental and operational conditions remain uniform throughout the period under consideration. The portion of concern in the entrance channel is 3 nautical miles and the normal transit

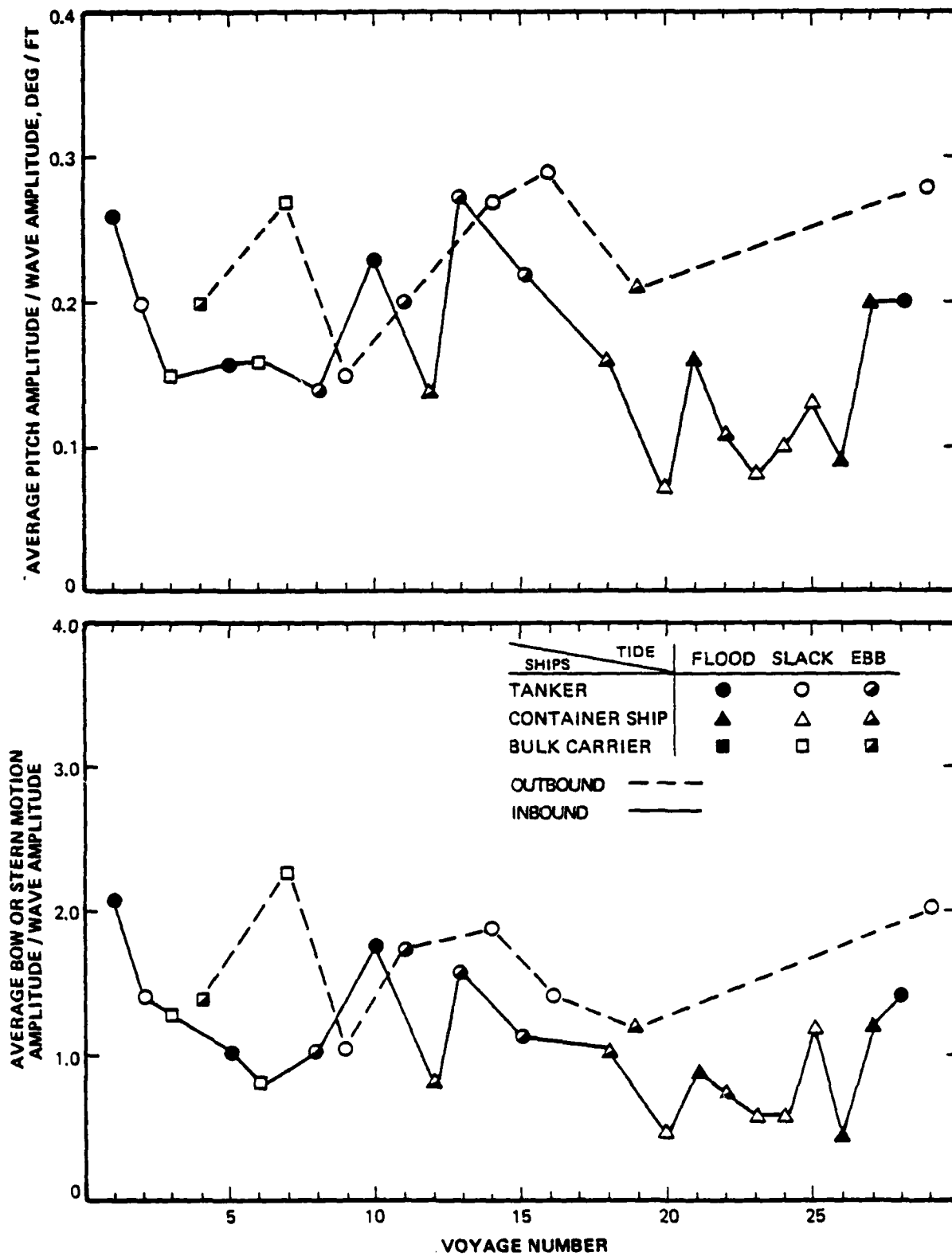


FIGURE 17a COMPARISON OF VESSEL RESPONSES (PHASE II)

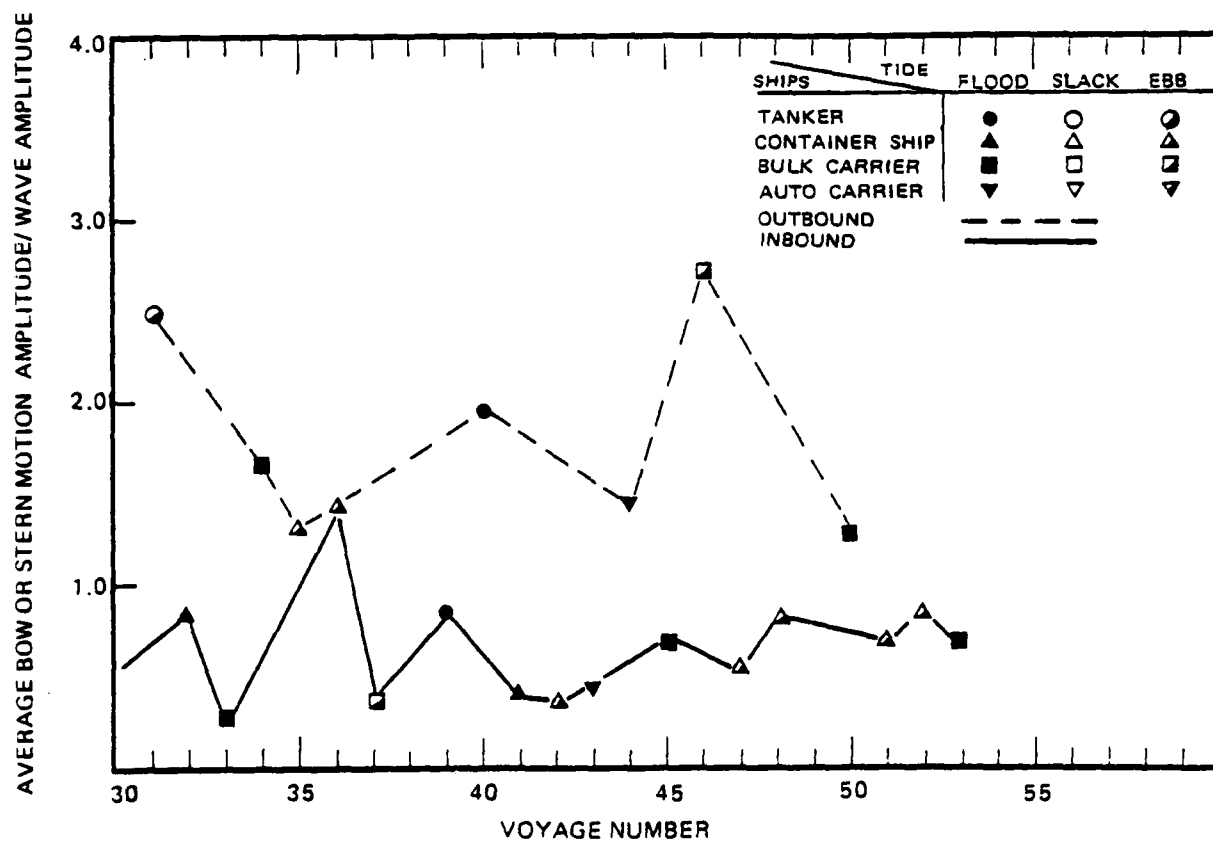
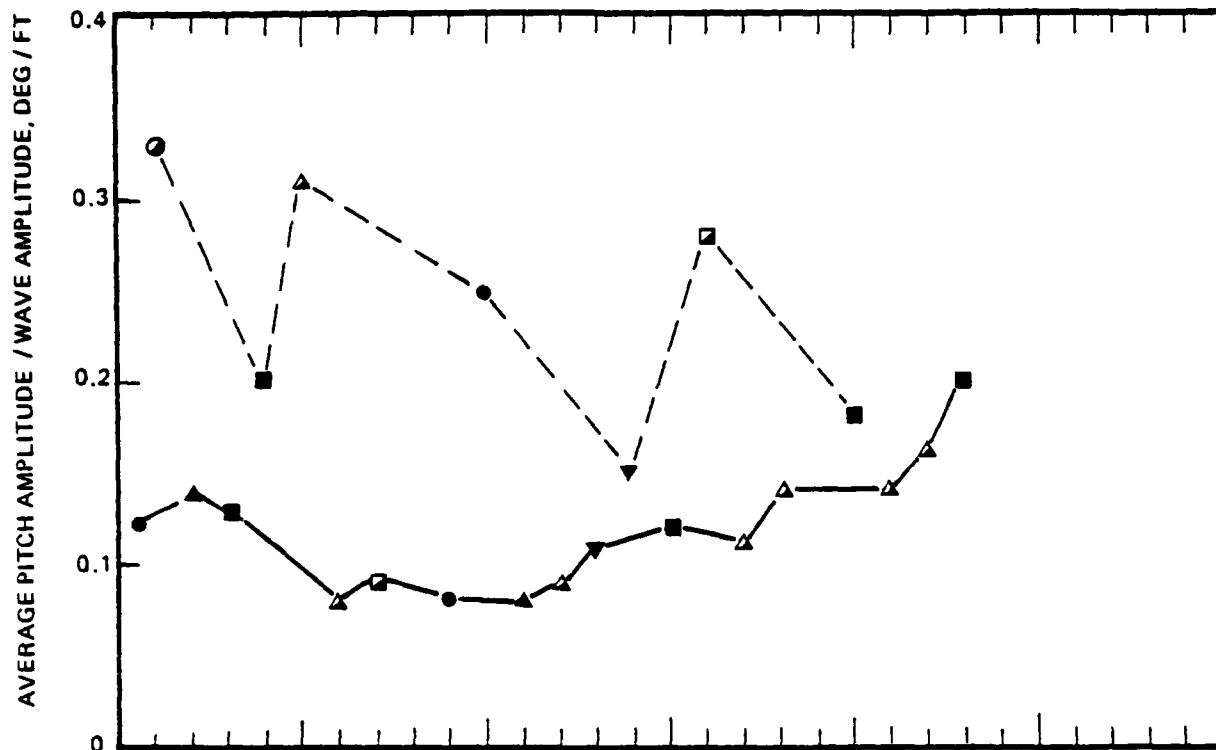


FIGURE 17b COMPARISON OF VESSEL RESPONSES (PHASE II)

duration for those ships under consideration is about 20 minutes. During this short distance and short duration, no significant changes in sea, tide and wind conditions are anticipated. Assuming further that the ship speed remains uniform during the transit, the statistics of the Rayleigh distribution are anticipated to be applicable to the analysis of the present data.

It is known that the Rayleigh distribution is a one parameter distribution defined by the mean square of the variate, E , as described in Equation (6). After the value of E is processed for a given sample, the theoretical distribution is immediately defined, to which the histogram of the measured sample can be compared. Sample histograms and theoretical Rayleigh distribution for pitch, roll, heave and bow excursion for Voyage No. 1 are shown in Figure 18.

In order to test the validity of the hypothesis, the method of the Chi-square test is normally applied. Since the cumulative probability of the Rayleigh distribution is given by

$$P(x_i) = 1 - e^{-x_i^2/E} = 1 - e^{-(x_i/x_{rms})^2}$$

as shown in Equation (8), the probability of exceedance $1 - P(x_i)$, can be plotted against the variable $(x_i/x_{rms})^2$ as a straight line on a semi-logarithmic paper. Consequently, if the measured sample is Rayleigh distributed, the sample distribution must follow closely with the theoretical straight line. It is considered that the latter method is much simpler than the Chi-square test, so tests of significance by the latter method are applied for several typical cases.

Figure 19 shows the tests performed for Voyage Nos. 1, 7, 15, and 23. These voyages are selected to represent various ship groups; for instance, Voyage No. 1 a tanker, No. 7 a bulk carrier and No. 23 a container ship. Voyage No. 15 represents a smaller tanker and the roughest sea conditions recorded during the period of the field program. From these plots it is

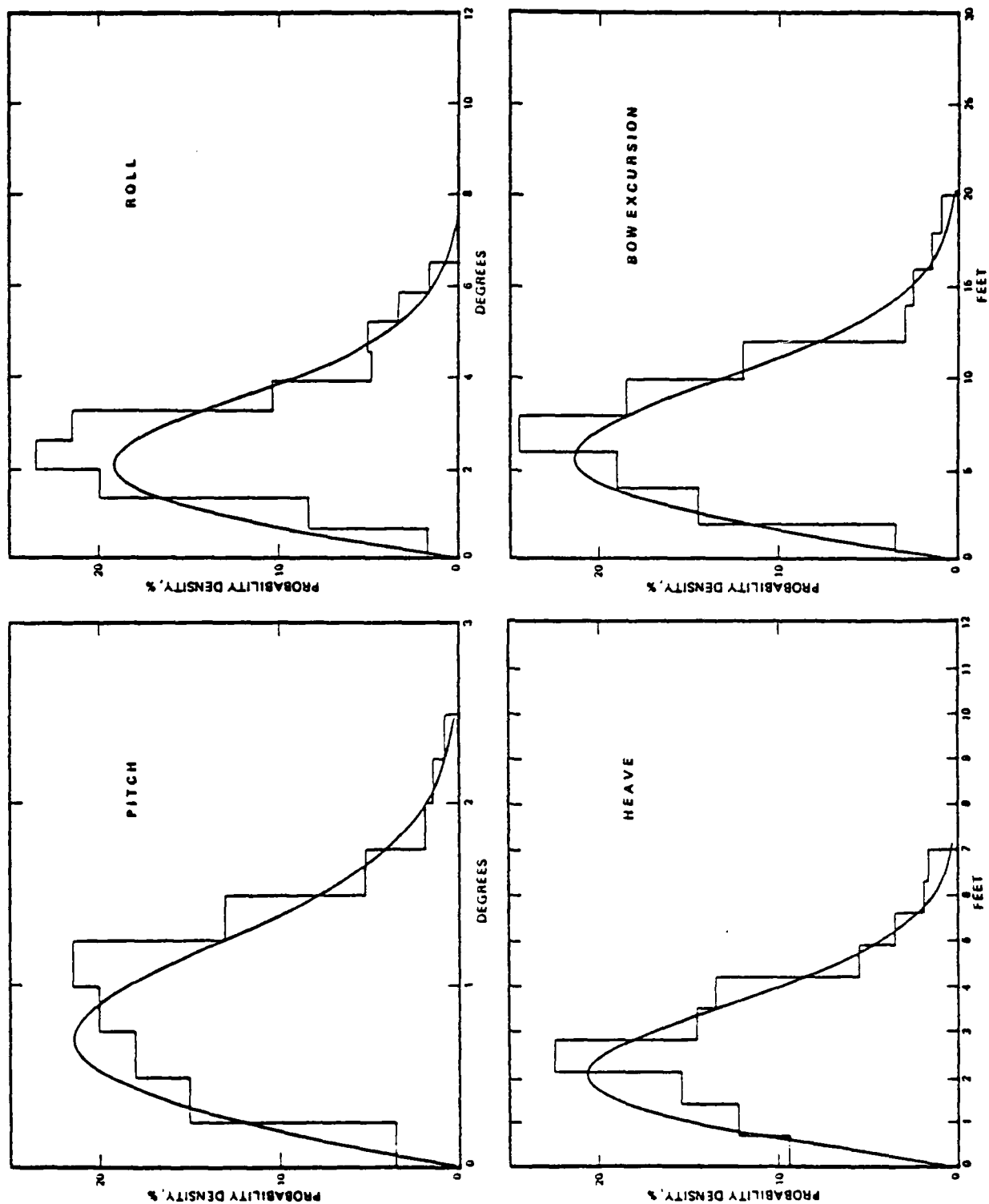


FIGURE 18 -- SAMPLE HISTOGRAMS AND THEORETICAL RAYLEIGH DISTRIBUTIONS (VOYAGE NO. 1)

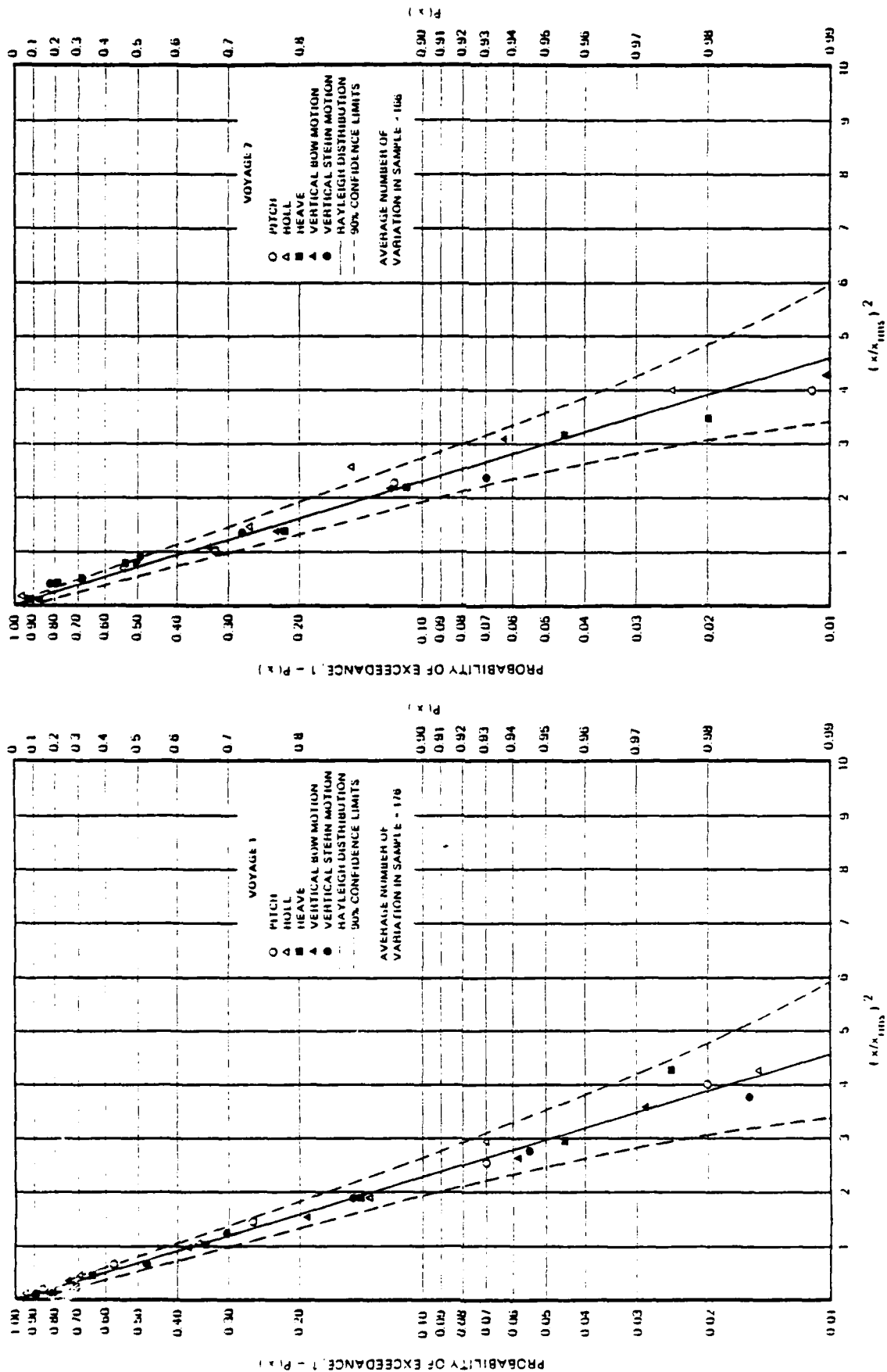


FIGURE 19a -- CUMULATIVE DISTRIBUTIONS OF MOTION VARIABLES FOR SELECTED VOYAGES

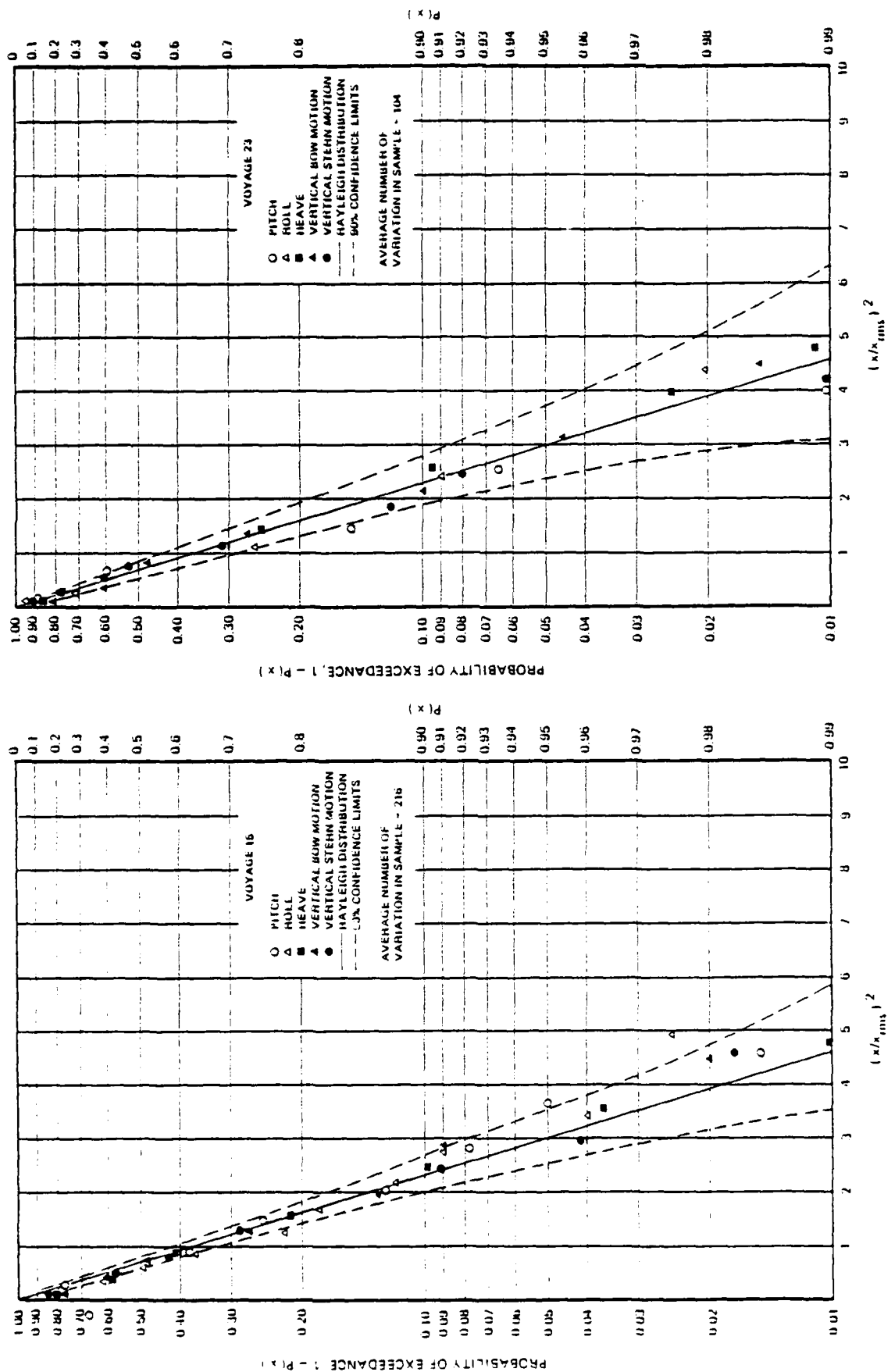


FIGURE 19b - CUMULATIVE DISTRIBUTIONS OF MOTION VARIABLES FOR SELECTED VOYAGES

seen that the measured data fall well within the 90 percent confidence limits. It appears evident, at least for those voyages tested, that there are no significant contradictions to the hypothesis that the measured data are samples from a Rayleigh distribution.

The tests of significance are not applied separately to each of the 53 voyages. Instead, assuming that all the measured data are samples from a Rayleigh distribution, the average and the highest measured values are compared with those predicted by the statistical theory. It is known that the average and the largest probable values are each related to the rms value of a Rayleigh distribution by a constant, as shown below [13]:

$$\begin{aligned}\text{average amplitude} &= 0.886 x_{\text{rms}} \\ \text{most probable maximum amplitude in} \\ N \text{ oscillations} &= (\log N)^{1/2} x_{\text{rms}}\end{aligned}$$

Table 11a gives the comparison of predicted and measured values of a number of parameters for the Phase I voyages. Whereas discrepancies exist in some cases, in general there appears to be satisfactory agreement between measured and predicted values. Similar results are indicated in the Phase II analysis as shown in Table 11b.

The preceding analysis provides a preliminary foundation that, for any given set of steady conditions, the vessel motions over the entrance channel are distributed in general accordance with the Rayleigh law of distribution. On this basis, motions can be predicted with a high degree of confidence if the rms values of various motion parameters are known for a ship under a given condition. Since analysis of this kind would involve a number of different ships and a great number of sea conditions, the utilization of analytical or experimental studies to systematically investigate the rms motion variations will be of great value to the long range program of the present study effort.

TABLE 11a
COMPARISON OF MEASURED AND
PREDICTED VALUES OF MOTION PARAMETERS
(PHASE I)

NO. OF SAMPLE NUMBER	PITCH				ROLL				VERTICAL EXTENSION†			
	AVERAGE AMPLITUDE (DEG)		NUMBER OF VARIATIONS IN SAMPLE	MAXIMUM AMPLITUDE (DEG)	AVERAGE AMPLITUDE (DEG)		NUMBER OF VARIATIONS IN SAMPLE	MAXIMUM AMPLITUDE (DEG)	AVERAGE AMPLITUDE (FT)		NUMBER OF VARIATIONS IN SAMPLE	MAXIMUM AMPLITUDE (FT)
	MEASURED	PREDICTED			MEASURED	PREDICTED			MEASURED	PREDICTED		MEASURED
1	1.0	0.89	164	2.5	2.7	2.57	171	6.4	7.1	7.09	174	20.2
2	0.6	0.53	148	1.3	1.1	1.15	115	2.9	4.2	4.16	164	10.4
3	0.4	0.35	145	0.7	0.6	0.62	115	1.4	2.9	2.87	175	6.3
4	0.4	0.35	149	1.0	0.4	0.35	114	1.3	2.8	2.82	203	9.5
5	0.7	0.62	154	1.5	1.6	1.60	154	3.6	4.6	4.70	172	12.6
6	0.4	0.35	143	0.9	1.3	1.31	141	2.6	3.4	3.44	172	7.8
7	0.4	0.35	146	0.9	0.5	0.44	164	1.3	3.0	3.01	167	7.9
8	0.8	0.71	153	2.3	1.7	1.51	156	4.8	5.3	5.34	168	20.3
9	0.8	0.71	230	1.7	2.1	2.30	190	6.2	5.9	5.95	244	15.47
10	0.8	0.71	152	1.2	1.1	1.11	143	2.1	5.3	5.49	165	15.0
11	0.5	0.44	166	1.2	0.7	0.71	151	2.1	4.2	4.16	193	10.6
12	0.4	0.35	147	0.8	1.1	1.42	110	2.1	2.4	2.40	153	6.3
13	0.4	0.35	147	0.8	0.8	0.80	111	2.3	2.4	2.66	231	6.9
14	1.3	1.2	225	2.9	3.0	3.03	222	13.4	8.5	8.58	241	22.72
15	2.1	1.86	178	6.0	4.4	4.78	238	17.5	9.8	10.28	189	32.6
16	2.6	2.30	304	4.9	5.8	5.67	272	11.0	11.4	11.16	296	30.06
17	0.3	0.27	45	0.7	0.8	0.80	39	1.9	1.5	1.50	90	4.6
18	0.5	0.44	111	1.7	1.1	1.06	88	2.6	2.6	2.54	153	7.40
19	0.5	0.44	209	5.2	4.4	4.78	163	14.5	10.8	11.16	229	29.37
20	0.5	0.44	90	1.2	2.7	2.66	84	5.7	2.5	2.75	129	6.83
21	0.8	0.71	88	1.8	3.1	3.10	82	11.7	4.4	4.70	116	12.3
22	0.7	0.62	88	1.5	3.1	3.10	82	8.1	4.2	4.52	98	11.8
23	0.5	0.44	98	1.1	1.7	1.68	70	5.6	2.9	3.01	129	7.50
24	0.3	0.27	131	0.8	2.0	2.00	110	4.3	1.8	1.95	196	5.05
25	0.4	0.35	97	0.9	2.7	2.66	88	6.0	2.1	2.22	137	5.9
26	0.3	0.27	44	0.6	1.3	1.33	63	2.8	1.6	1.60	100	3.4
27	0.5	0.44	83	0.9	2.2	2.22	84	5.4	3.0	3.10	126	7.2
28	0.7	0.62	144	1.6	1.4	1.51	181	3.6	4.3	4.61	189	14.6
29	0.8	0.71	310	1.8	1.0	1.06	286	4.7	5.1	5.12	356	15.2

† Excursions are at low unless otherwise indicated.

* Data calculation.

TABLE 11b
COMPARISON OF MEASURED AND
PREDICTED VALUES OF MOTION PARAMETERS
(PHASE II)

DATA NUMBER	PITCH			ROLL			VERTICAL EXCURSION [†]		
	SAMPLED RMS AMPLITUDE (DEG)	AVERAGE AMPLITUDE (DEG)		SAMPLED RMS AMPLITUDE (DEG)	AVERAGE AMPLITUDE (DEG)		SAMPLED RMS AMPLITUDE (FT)	AVERAGE AMPLITUDE (FT)	
		MEASURED	PREDICTED		MEASURED	PREDICTED		MEASURED	PREDICTED
10	0.3	0.3	0.27	0.4	0.4	0.44	1.6	1.4	1.42
11	1.6	1.5	1.42	2.8	2.8	2.75	12.5	11.4	11.08
12	0.5	0.5	0.44	1.4	1.4	1.39	3.3	2.8	2.92
13	0.2	0.2	0.18	0.4	0.4	0.39	1.1	1.18	1.15
14	0.6	0.6	0.53	1.4	1.4	1.39	5.6	5.0	4.96
15	1.2	1.1	1.06	2.9	2.8	2.87	7.6*	6.7	6.73
16	0.3	0.3	0.27	0.7	0.66	0.66	2.0	1.7	1.77
17	0.3	0.3	0.27	0.6	0.6	0.60	1.5	1.2	1.33
18	--	--	--	--	--	--	--	--	--
19	0.2	0.2	0.18	0.4	0.4	0.44	0.9*	0.8	0.8
20	1.1	1.0	0.97	2.1	2.1	2.03	8.9	7.9	7.89
21	0.3	0.3	0.27	0.5	0.5	0.51	1.3	1.0	1.15
22	0.3	0.3	0.27	1.0	1.0	1.13	1.7	1.5	1.57
23	0.4	0.4	0.35	1.0	1.0	0.97	2.6*	2.4	2.30
24	1.2	1.0	1.06	3.0	2.9	2.97	6.1	5.6	5.6
25	0.4	0.3	0.35	0.9	0.89	0.89	1.7	1.7	1.78
26	0.8	0.7	0.71	2.8	2.8	2.72	2.0*	1.7	1.77
27	0.4	0.4	0.35	1.1	1.1	1.08	7.3	6.8	6.47
28	0.5	0.5	0.44	1.7	1.7	1.75	2.3	2.0	2.02
29	--	--	--	--	--	--	3.7	2.9	3.28
30	1.0	0.8	0.89	2.2	2.2	2.16	--	--	--
31	0.6	0.5	0.53	1.6	1.6	1.51	7.3	5.9	6.47
32	0.8	0.7	0.71	2.4	2.4	2.36	4.5**	4.0	3.99
33	0.3	0.3	0.27	0.5	0.5	0.62	4.7	3.8	4.16
34	0.3	0.3	0.27	0.5	0.5	0.62	1.2*	1.0	1.06

[†] Excursions are at low unless otherwise indicated.

* Stern.

** Side.

-- No data due to equipment failure.

Whereas the individual transits are shown to follow the Rayleigh distribution, it is desirable to know if any particular pattern in long term statistics can be derived from the measured data, so that a statistical prediction can be made for a wide variety of conditions. For this purpose, each distribution of the measurements is weighted in accordance with the probability of sea conditions that may occur in the area so as to construct the long term distribution patterns of vessel motions applicable to the Columbia River Entrance Channel. In the following, the Phase I data are first discussed and then an analysis of the combined Phase I and Phase II data is presented.

As discussed in previous sections, the wave conditions observed are mainly due to long period swells. Local wind generated seas have rarely shown to be as important as swells in all of the 53 voyages. Consequently, only the swell height and direction are considered here. The annual height and direction distributions of swell in this area have been compiled by National Marine Consultants [11] and have been shown in Figures 8 and 10. According to these distributions, wave heights and directions are classified into several categories and the joint probabilities of occurrence are determined. The results are summarized below.

These joint probabilities represent the fractions of time that specified ranges of swell (heights and directions) will be experienced in the entrance channel region. Weighting the distribution of each individual transit by the appropriate factor, the long term distribution pattern of the vertical vessel excursions based upon the Phase I data is calculated and tabulated in Table 12.

It should be noted that the probability distribution of each transit is normalized by the number of variations corresponding to a constant distance of transit between buoy Nos. 2 and 8. The actual sampling numbers correspond to different distances and different locations of beginning and ending. To obtain the number of variations which would have been recorded for a

TABLE 12
CALCULATION OF DISTRIBUTION PATTERN FOR VARIATIONS
IN VERTICAL VESSEL EXCURSIONS
(PHASE I)

WAVE HEIGHT CLASS (FT)	OBSERVED WAVE HEIGHT AND DIRECTION				WEIGHTING FACTOR (f)	NUMBER OF VARIATIONS PER STAR- DORIZED TRANSIT (N)	AVERAGE NUMBER OF VARIATIONS ATTRIBUTED TO EACH TRANSIT (f/N)	PROBABILITY OF EXCEEDING GIVEN MAGNITUDE OF VARIATION X IN FT (FROM SAMPLE)										SAMPLED RMS VARIATION (ft)	NUMBER OF VARIATIONS IN SAMPLE	LOCATION OF MAXIMUM VERTICAL MOTION ON SHIP	VOYAGE NUMBER
	SWELL		SEA					1.0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0					
	DIRECTION	HEIGHT (FT)	DIRECTION	HEIGHT (FT)																	
0-3	W	SLIGHT*	SE	3	.091	233	21.20	58.7	33.1	2.1							2.5	233	bow	13	
	W	SLIGHT*	SE	3	.144	178	25.64	60.0	13.6								1.8	90	bow	17	
	WSW	1-3	W	SLIGHT	.028	203	5.76	83.0	51.5	10.4	1.6						3.3	203	bow	4	
	WSW	2-4	W	SLIGHT	.144	257	37.01	86.0	63.9	12.2	1.1						3.4	187	bow	7	
3-5	WSW	3-4	ESE	1-2	.002	143	0.29	75.7	41.3	1.2							2.5	137	bow	25	
	W	4	WSW	SLIGHT	.060	223	13.38	87.2	49.9	3.6							2.9	175	bow	3	
	W	5	NE	1-2	.092	225	20.70	94.9	79.4	32.1	8.2	1.5					4.7	193	bow	11	
	W	4-6	—	CALM	.092	238	21.90	86.3	56.2	14.0	1.0						3.4	172	bow	6	
5-7	WSW	4-6	WSW	SLIGHT	.096	216	20.7	69.4	46.6	14.0	1.4	0.8					3.3	153	stern	18	
	W	4-6	S	SLIGHT	.06	125	7.50	76.3	59.6	7.0							3.5	126	bow	27	
	W	4-6	—	CALM	.030	363	21.78	93.2	75.8	46.2	26.0	5.8	1.0				6.0	356	bow	29	
	W	6	NW	2-4	.03	208	6.54	93.2	77.4	41.8	7.0	0.5					4.7	164	bow	2	
7-9	NW	6	NW	2-4	.04	173	6.92	92.8	75.6	52.6	25.8	6.8	0.4				6.2	165	bow	10	
	WSW	6	SSE	SLIGHT	.008	138	1.10	75.0	43.2	6.2							2.8	153	bow	12	
	SSW	6	S	SLIGHT	.07	196	13.72	83.0	24.0	2.0							2.2	196	bow	24	
	WSW	6	—	CALM	.048	189	9.07	82.2	68.9	41.5	12.5	4.8	0.8				5.2	189	bow	28	
9-15	WSW	6-8	WSW	SLIGHT	.004	141	0.56	46.5	15.6								1.8	100	bow	26	
	NW	6-8	NW	2-4	.044	244	10.74	98.0	92.9	75.8	45.0	10.0	6.8	3.0	0.9	0.9	8.0	174	bow	1	
	WSW	8-10	NW	SLIGHT	.020	172	3.44	84.1	72.4	44.3	14.1	3.9					5.4	172	bow	5	
	WSW	8-10	NW	4-6	.02	254	5.08	96.0	88.9	76.0	58.3	32.3	18.6	10.1	4.0	1.5	9.7	241	bow	14	
15-20	NW	10	—	CALM	.016	159	2.54	87.0	72.6	47.5	21.9	13.1	8.0	3.8	0.6	0.6	6.7	168	bow	8	
	W	10	ENE	SLIGHT	.012	138	1.66	84.3	68.2	42.0	15.0	2.2					5.3	116	bow	21	
	W	10	E	SLIGHT	.024	152	3.65	82.0	55.1	9.9	1.5						3.4	129	bow	23	
	WSW	10-12	NW	2-4	.036	268	9.65	93.0	85.1	62.1	31.1	7.2	0.6				6.6	244	bow	9	
15-20	WSW	10-12	NW	SLIGHT	.004	158	0.63	69.4	43.1	11.4	1.1						3.1	129	bow	20	
	WSW	10-12	NE	SLIGHT	.016	152	2.43	86.9	65.5	33.1	15.0	4.1					5.1	98	bow	22	
	W	12-18	SSE	2-3	.012	391	4.69	95.0	91.0	80.2	65.6	55.3	36.4	18.3	9.2	5.1	12.6	296	stern	16	
	W	15-18	ESE	SLIGHT	.004	290	1.16	94.2	89.9	82.2	68.8	52.1	37.3	21.4	12.3	5.6	12.6	229	stern	19	
15-20	W	15-20	W	2	.004	186	0.74	93.2	87.6	77.8	60.6	43.3	30.1	19.8	10.5	4.4	11.6	189	stern	15	
	Number of variations exceeding given level							279.88	227.34	161.48	66.92	29.07	10.2	4.62	2.21	0.97	0.54				
Percentage of variations exceeding given level							279.88	81.2	57.7	23.9	10.4	3.6	1.7	0.8	0.3	0.2					

* Accurate observation precluded by darkness

Direction	Characteristic Wave Height ft						Total
	0-3	3-5	5-7	7-9	9-15	>15	
NNW	1.78	1.19	0.57	0.25	0.22	0.05	4.06
NW	13.78	9.21	4.44	1.96	1.70	0.41	31.49
WNW	14.40	9.62	4.64	2.05	1.77	0.43	32.91
W	9.05	6.05	2.92	1.29	1.12	0.27	20.69
WSW	2.84	1.89	0.91	0.40	0.35	0.08	6.48
SW	1.26	0.85	0.41	0.18	0.16	0.04	2.89
SSW	0.22	0.15	0.07	0.03	0.03	0.01	0.50
S	0.39	0.26	0.13	0.06	0.05	0.01	0.50
SSE	0.04	0.02	0.01	--	--	--	0.08
TOTAL	43.76	29.24	14.09	6.22	5.39	1.30	100

standardized transit, the sampled numbers are proportionally adjusted according to the ratio of the distance between buoy Nos. 2 and 8 and the distance used in sampling.

The last line in the table is obtained by summing up, for each tabulated magnitude of variation, the products of the exceedance probability and the average number of variations attributed to each transit and then dividing by the total average number of variations on 29 transits combined. The results, which reflect the weighting due to wave distribution as well as the normalization according to the transit distance, thus represent derived values for a long term distribution. The values are plotted on a log-probability chart and shown in Figure 20. The good fit of the plotted points to a straight line suggests that the measured data can be approximated by a log-normal distribution. (The straight line is not an arbitrary fit but is actually computed from the plotted points as shown in Table 13).

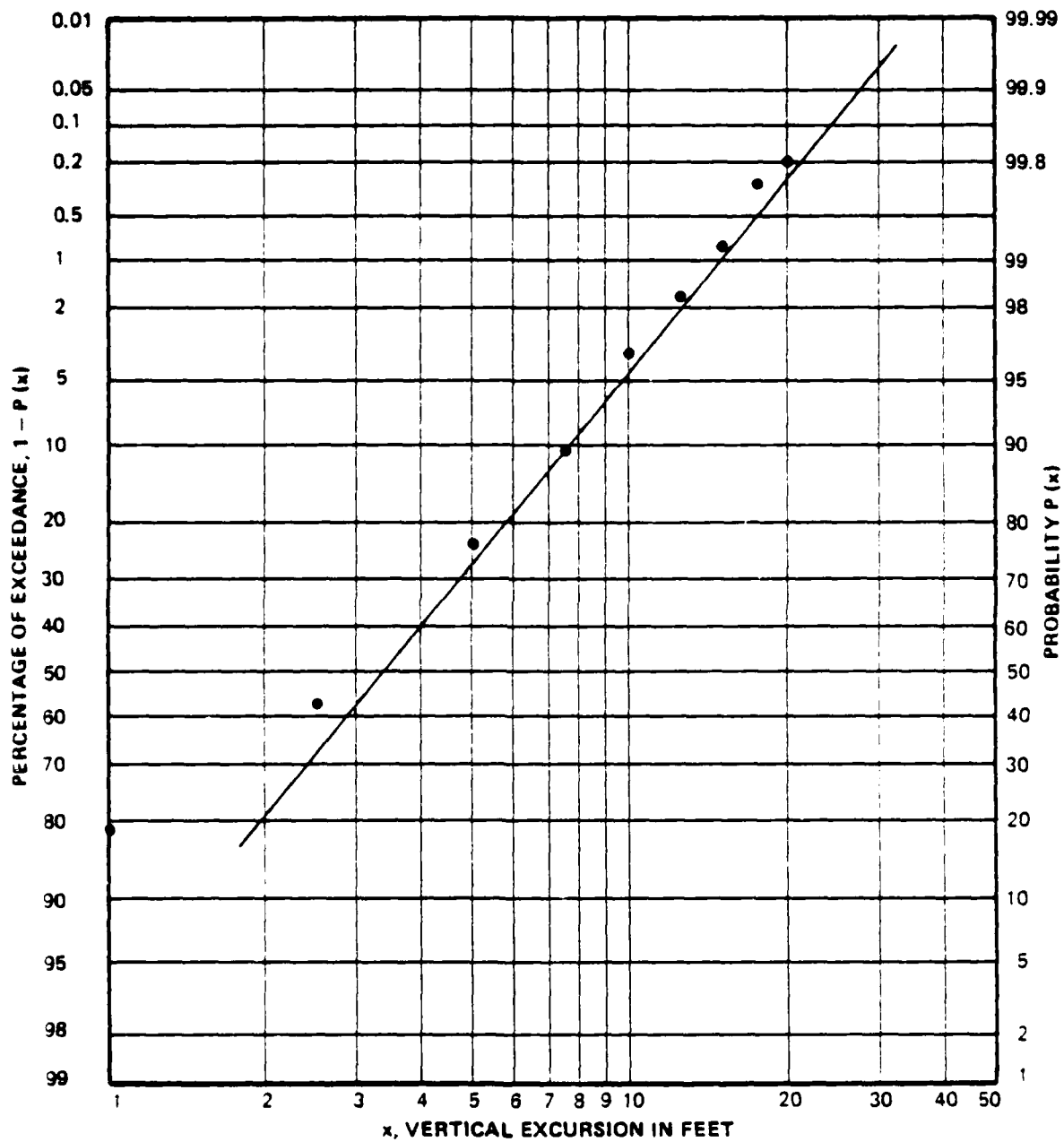


FIGURE 20 STATISTICAL DISTRIBUTION OF VERTICAL VESSEL MOTIONS (PHASE I DATA)

TABLE 13
COMPUTATION FOR FITTING A THEORETICAL LOG-NORMAL DISTRIBUTION
TO MEASURED DATA ON VERTICAL VESSEL EXCURSIONS
(PHASE I DATA)

CLASS OF VERTICAL EXCURSION ft x	LOG ₁₀ x AT END OF CLASS INTERVAL	CENTER OF CLASS INTERVAL h	h^2	PERCENTAGE OF VARIATION FALLING WITHIN CLASS N	Nh^2	Nh
1.0	0.	.1989	.0396	23.5	0.9306	4.6742
2.5	0.3979	.5485	.3009	33.8	10.1700	18.539
5.0	0.6990	.7871	.6195	13.5	8.3633	10.626
7.5	0.8751	.9376	.8791	6.8	5.9779	6.3757
10.	1.0000	1.0485	1.0994	1.9	2.0889	2.1902
12.5	1.0969	1.1365	1.2916	0.9	1.1624	1.0229
15.	1.1761	1.2090	1.4631	0.5	.7316	.6045
17.5	1.2430	1.2720	1.6180	0.1	.1618	.1272
20.	1.3010					
				$\Sigma = 81.0$	29.5865	44.1597

$$y = \frac{2Nh^2 \cdot \Sigma N}{2(Nh)^2} = 0.6145$$

$$z = -1.865^*, q(z) = .5163^*$$

$$\text{standard deviation of } h \quad \sigma = s = \frac{2Nh}{\Sigma N} \cdot q(z) = 0.2815$$

$$\text{mean value of } h = -zs = 0.525$$

$$\text{mean value of } x = 3.35 \text{ ft}$$

*Reference [14]

The preceding analysis also suggests that long term predictions of vertical excursions could be approximated by a log-normal distribution with a high degree of success. In fact, Figure 20 shows that there should be only one per cent of probability, on the average, that the vertical excursion (bow or stern) would exceed 15 ft. It should be noted, however, that due to the limited number of measured data, the analysis presented above does not reflect any differences between various types of vessels. In other words, all ships have been considered identical in the long term statistical analysis.

As indicated earlier, the foregoing analysis was based upon the Phase I data and thus the statistical distribution developed pertains to the environmental conditions that the data represents. In order to extend the data base, an analysis based upon the combined data of Phase I and Phase II is conducted. Similar to Table 12, the calculation of the distribution pattern for the combined data is presented in Table 14. The results indicate again that a good approximation by log-normal distribution to the measured data can be made as shown in Figure 21. As compared with the Phase I results presented in Figure 20 (shown as a dotted line in Figure 21), the probability distribution is slightly higher at the lower amplitudes but fairly close at the higher motion amplitudes. For instance, the probability of the vertical excursion to exceed 15 ft is again on the order of one percent. Consequently, the Phase II data seem to confirm the Phase I results developed previously.

7.5 EXTREME VALUE DISTRIBUTIONS

The previous analysis demonstrates that ship motions in the channel follow very closely the basic pattern of logarithmical-normal distribution. It should be understood, however, that the long term probability is derived based upon the duration of all transits over the interval between buoy Nos. 2 and 8, and the cumulative distribution function so obtained must also be

TABLE 14
CALCULATION OF DISTRIBUTION PATTERN FOR VARIATIONS
IN VERTICAL VESSEL EXCURSIONS
(PHASE I AND II)

WAVE HEIGHT CLASS (FT)	OBSERVED WAVE HEIGHT AND DIRECTION				WEIGHTING FACTOR (F)	NUMBER OF VARIATIONS PER STAN- DARDIZED TRANSIT (N)	AVERAGE NUMBER OF VARIATIONS ATTRIBUTED TO EACH TRANSIT (E/N)	PROBABILITY OF EXCEEDING GIVEN MAGNITUDE OF VARIATION X IN FT. (FROM SAMPLE)											SAMPLED RMS VARIATION (ft)	NUMBER OF VARIATIONS IN SAMPLE	LOCATION OF MAXIMUM VERTICAL MOTION ON SHIP	VOYAGE NUMBER
	SWELL		SEA					1.0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0						
	DIRECTION	HEIGHT (FT)	DIRECTION	HEIGHT (FT)																		
3-3	M	SLIGHT*	SE	3	.091	233	21.20	58.7	33.1	2.1					2.5	233	BOW	11				
	M	SLIGHT*	SE	SLIGHT CHOP	.144	178	25.64	60.0	13.6						1.8	90	BOW	17				
	WSW	1-3	M	SLIGHT CHOP	.028	203	5.76	93.0	51.5	10.4	1.6				3.3	203	BOW	4				
	WSW	4-4	M	SLIGHT CHOP	.144	257	37.31	36.1	51.9	12.2	1.1				3.4	187	BOW	7				
	M	2-4	M	SLIGHT CHOP	.091	303	27.57	74.5	46.3	15.0	4.2	2.5			3.7	303	BOW	40				
	M	2-4	E	SLIGHT CHOP	.091	177	16.15	49.5	4.0						1.2	183	STERN	53				
	M	2-4	E	1-2	.091	237	21.57	60.0	2.0						2.3	137	BOW	33				
	SSW	3-4	ESE	1-2	.002	143	3.29	75.7	41.3	1.2					2.5	137	BOW	45				
3-5	M	4	WSW	SLIGHT CHOP	.060	223	13.38	47.2	49.9	3.6					2.9	175	BOW	1				
	SSW	3-5	—	SLIGHT CHOP	.002	197	3.39	43.5	7.3						1.3	197	BOW	41				
	WSW	5	NE	1-2	.092	225	20.70	34.9	79.4	32.1	8.2	1.5			4.7	193	BOW	12				
	M	3-6	—	SLIGHT CHOP	.062	194	11.84	71.0	21.3	4.7					2.1	211	BOW	36				
	WSW	4-6	—	CALM	.092	238	21.90	86.3	56.2	14.0	1.0				3.4	172	BOW	6				
	WSW	4-6	WSW	SLIGHT CHOP	.096	216	20.7	69.4	46.0	14.0	1.4	0.8			3.3	153	STERN	18				
	M	4-6	S	SLIGHT CHOP	.06	125	7.50	76.3	59.6	7.0					2.3	126	BOW	27				
	N	4-6	—	CALM	.030	363	21.78	93.2	75.8	46.2	26.0	5.8	1.0		6.0	156	BOW	29				
	WSW	5	S	1-2	.092	167	13.76	51.2	18.5						1.6	153	BOW	30				
	M	4-6	E	2-3	.061	167	12.39	46.5	2.5						2.9	167	STERN	29				
	M	4-5	E	2-3	.061	67	4.09	71.2	19.3						1.0	67	STERN	45				
	SW	4-6	E	2-4	.009	88	1.80	39.2	36.1	68.3	40.9	12.8	2.7	2.0	2.4	45	BOW	46				
	M	4-6	E	2-3	.061													49				
3-7	WSW	6	—	CALM	.048	189	3.37	42.4	68.9	41.5	12.5	4.6	2.8		5.2	189	BOW	18				
	WSW	6	SSE	SLIGHT CHOP	.008	138	1.10	75.0	43.4	9.4					1.8	131	BOW	12				
	SSW	6	S	SLIGHT CHOP	.07	196	13.72	63.0	24.0	2.0					2.1	196	BOW	14				
	M	6	M	1-2	.029	247	7.17	36.0	41.0	45.0	19.0	3			5.6	131	BOW	16				
	M	6	SW	2-3	.03	108	6.24	93.2	77.4	31.8	7.0	2.5			4.7	164	BOW	17				
	WSW	6-8	WSW	3-4	.04	173	6.92	75.0	52.6	25.8	6.8	2.4			6.1	165	BOW	17				
	M	6-8	—	SLIGHT CHOP	.009	141	3.56	46.5	15.6						4.8	117	BOW	26				
	WSW	6-8	—	SLIGHT CHOP	.029	148	4.29	35.6	46.1	15.1					3.1	151	BOW	32				
	WSW	6-8	—	SLIGHT CHOP	.046	164	10.50	70.0	3.5	5					2.5	164	STERN	42				
	SW	6-8	ESE	1-2	.004	132	1.33	44.9	88.0	68.5	41.0	19.0	4.0	2.0	5.1	132	BOW	35				
	M	6-8	ESE	4	.029	228	6.62	41.0	9.8	1.5					1.3	144	BOW	37				
	M	6-8	—	SLIGHT CHOP	.029	49	1.42	35.0	36.0	21.3					2.0	44	STERN	43				
	WSW	6-8	E	1-2	.046	183	8.41	71.2	31.8	2.5					1.3	119	BOW	47				
	WSW	6-8	WSW	2-4	.046	279	12.85	90.0	76.5	22.5	6.8	2.5			3.1	191	BOW	52				
	WSW	6-8	WSW	2-4	.044	244	10.74	98.1	92.9	75.8	45.0	10.0	6.8	3.0	6.5	174	BOW	52				
3-9	—	SLIGHT	S	6-10	.001													58				
	WSW	8-10	SW	SLIGHT CHOP	.020	172	3.44	91.0	72.4	44.3	41.1	3.9			5.4	171	BOW	1				
	M	8-10	—	SLIGHT CHOP	.013	129	1.98	97.1	93.5	86.1	72.0	60.0	43.0	29.0	13.5	4.1	125	BOW	2			
	WSW	9-10	WSW	4-6	.02	254	5.38	36.1	88.9	76.1	58.7	32.3	18.6	10.1	4.0	1.3	4.1	14				
	SW	9	SSE	4	.002	113	.43	35.5	48.1	73.1	51.5	33.5	14.4	4.5	9.9	179	BOW	4				
	WSW	9-10	SW	1-2	.021	136	.96	97.1	93.2	82.1	66.5	52.0	37.8	21.0	5	1.1	143	BOW	7			
3-15	WSW	9-10	E	1-2	.021	165	3.56	90.0	61.2	31.0	4.3	1.5	1.0	0.8	4.1	174	BOW	8				
	WSW	10	—	CALM	.016	159	1.54	97	72.8	47.5	21.9	23.1	9.1	1.8	6	1.7	168	BOW	9			
	M	10	ESE	SLIGHT CHOP	.012	138	1.66	94.1	98.2	42.0	15.0	2.4			6.1	127	BOW	11				
	M	10	E	SLIGHT CHOP	.024	152	1.65	42.0	55.1	9.9	1				2.4	123	BOW	13				
	WSW	10-12	WSW	2-4	.036	268	4.65	91.1	85.1	62.0	31.1	7.2	1.8		6.6	144	BOW	14				
	WSW	10-12	WSW	SLIGHT CHOP	.016	158	1.61	69.4	43.1	11.4	1.1				1.1	127	BOW	15				
	WSW	10-12	NE	SLIGHT CHOP	.016	152	2.43	96.9	65.5	33.1	15.0	4.1			3.1	146	BOW	16				
	M	10-15	WSW	6-7	.004	167	1.67	98.5	95.8	78.4	44.1	23.9	14.4	4.1	9.1	157	BOW	44				
	M	12-18	SSE	2-3	.012	391	4.69	95.1	91.1	80.1	65.6	55.1	36.4	18.1	4.1	1.9	196	STERN	16			
> 15	M	15-18	ESE	SLIGHT CHOP	.004	290	1.16	94.1	49.9	42.1	68.8	52.1	37.1	13.4	1.1	1.5	129	STERN	19			
	M	17-20	M	2	.004	186	1.74	91.1	87.4	77.8	60.6	43.9	36.1	19.8	10.5	4.4	119	STERN	21			
Number of variations exceeding given level							487.73	160.77	121.83	88.47	44.67	14.66	4.7	1.14	1.42	64						
Percentage of variations exceeding given level							73.4	45.5	36.1	24.1	11.4	3.4	1.1	1.1	1.1							

* No data due to equipment failure

* Accurate observation precluded by darkness

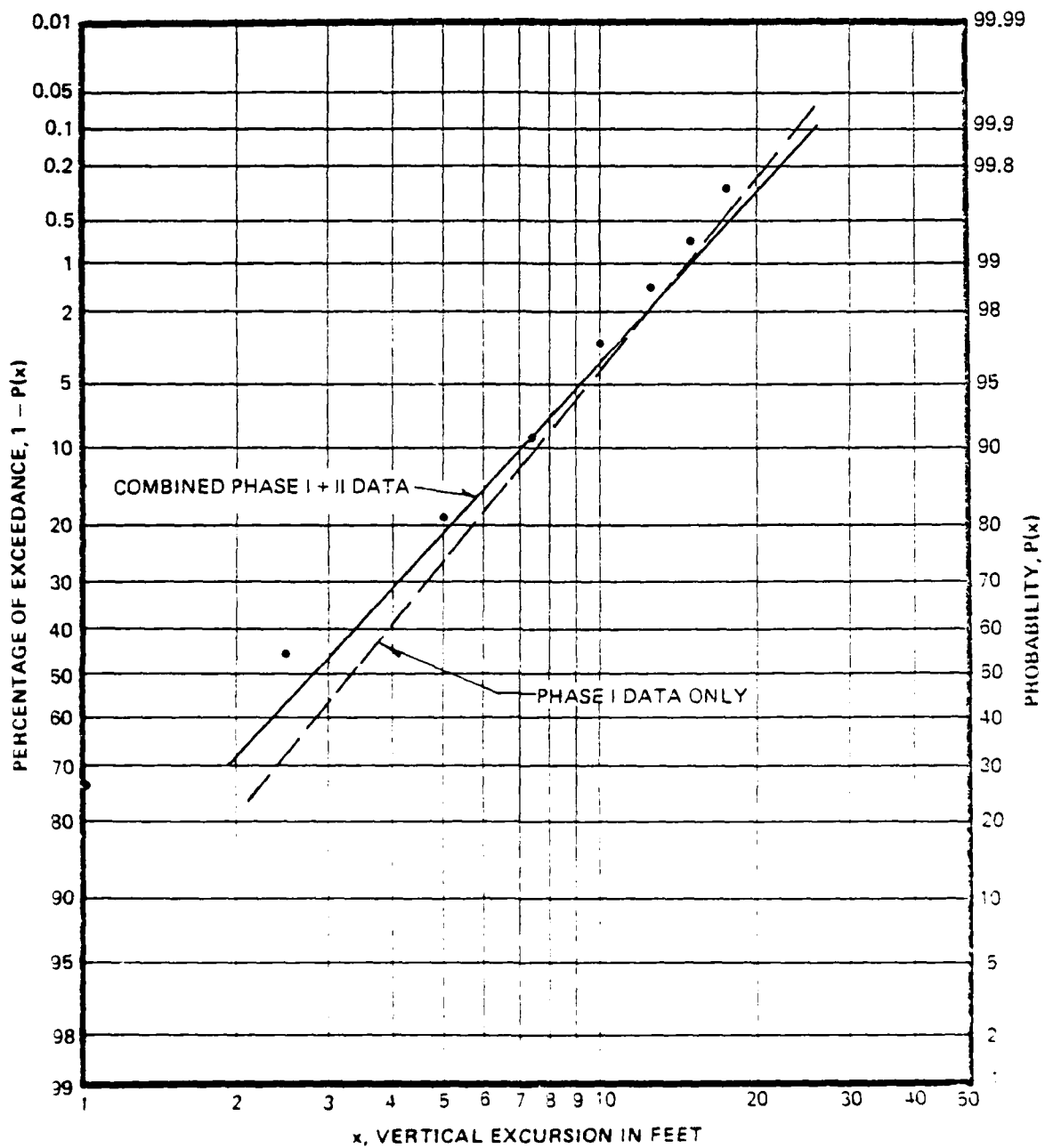


FIGURE 21 STATISTICAL DISTRIBUTION OF VERTICAL VESSEL MOTIONS (PHASE I AND II DATA)

interpreted on the same basis. For instance, as has been concluded, on the average the probability of the vertical ship excursion to exceed 15 ft over the entrance channel is less than 1%. This 1% exceedance probability is applied to the total of all the transits of the classes of ships considered over a long period of time. For a particular transit, however, the probability of occurrence of 15 ft excursion is not definitely known before the environmental condition is exactly defined; it may be much higher or lower than 1% or simply may not even exist. It is often not necessary to know how long a prescribed level of motion would last, but more desirable to know what is the largest value of ship excursion which may occur during a single transit and how frequent in terms of voyages this largest value would occur. For this purpose, the analysis of extreme value distribution is required.

It is known [15] that if the underlying distribution is normal or logarithmically normal, the largest values in repeated samples from this distribution would have a cumulative distribution of their own. As the number of samples becomes large, the cumulative distribution function of the largest values will approach asymptotically to the form

$$P(x) = \exp [-e^{-y}] \quad (23)$$

where $y = a(h - b)$, the reduced variate, and $h = \log x$ if the underlying distribution is logarithmically normal. The variate x is a possible value of the extreme of the sampled variable, and a and b are constants for a particular distribution. The determination of these constants based upon the distribution of extremes obtained from measurements has been discussed in [15].

The application of this method to the extreme vertical motions measured over the 29 transits of Phase I is shown in Table 15 and the resulting extreme value distribution is plotted in Figure 22. Inspection of this figure shows that, for the environmental conditions encountered, the extreme value distribution

TABLE 15
COMPUTATION FOR FITTING A THEORETICAL EXTREME VALUE DISTRIBUTION
TO MEASURED DATA ON VERTICAL VESSEL EXCURSIONS
(PHASE I DATA)

EXTREME DOWNWARD EXCURSION ft x	$\log_{10} x$ h	NUMBER OF OBSERVATIONS n	RANK m	$P(x)$ $\frac{m}{N+1}$	$ h-\bar{h} $	$(h-\bar{h})^2$	VOYAGE NUMBER
3.9	.5911	1	1	.033	.4066	.1653	26
4.2	.6232	1	2	.067	.3745	.1402	17
4.3	.6335	1	3	.1	.3642	.1326	24
4.4	.6435	1	4	.133	.3542	.1254	25
5.7	.7559	1	5	.167	.2418	.0585	3
6.2	.7924	1	6	.2	.2053	.0421	12
6.9	.8388	2	7.48	.249	.1589	.0252	13, 27
7.0	.8451	1	9	.3	.1526	.0233	6
7.6	.8808	1	10	.333	.1169	.0137	20
7.7	.8865	1	11	.367	.1112	.0124	18
8.1	.9085	3	12.96	.432	.0892	.0080	4, 7, 23
10.4	1.0170	1	15	.5	.0193	.0004	2
10.6	1.0253	1	16	.533	.0276	.0008	11
11.7	1.0682	1	17	.567	.0705	.0050	22
11.8	1.0719	1	18	.6	.0742	.0055	5
12.0	1.0792	1	19	.633	.0815	.0066	28
12.3	1.0899	1	20	.667	.0922	.0085	21
13.9	1.1430	1	21	.7	.1453	.0211	9
15.0	1.1761	1	22	.733	.1784	.0318	10
15.2	1.1818	1	23	.767	.1841	.0339	29
17.0	1.2304	1	24	.8	.2327	.0542	1
20.3	1.3 75	1	25	.833	.3098	.0960	8
21.9	1.3404	1	26	.867	.3427	.1175	15
22.0	1.3424	1	27	.9	.3447	.1188	14
24.8	1.3945	1	28	.933	.3968	.1575	19
25.7	1.4099	1	29	.967	.4122	.1700	16
$\Sigma = 28.9326$				$\Sigma = 1.6155$			

$N = 29$

Observed Average:

$$\bar{x} = \frac{\Sigma x}{N} = \frac{28.9326}{29} = 1.000$$

Observed Standard Deviation:

$$s = \sqrt{\frac{\Sigma x^2 - \frac{(\Sigma x)^2}{N}}{N-1}} = 1.10$$

Expected average and standard deviation
of reduced variate y for a given N :

$$\bar{y}_N = 0.5853$$

$$s_N = 1.1366$$

$$1 + \frac{N}{s} = 1.0975$$

$$2 + \frac{N}{s} = 1.0975$$

Best fit: $y = 1.0975 - 0.807$

*Reference [15]

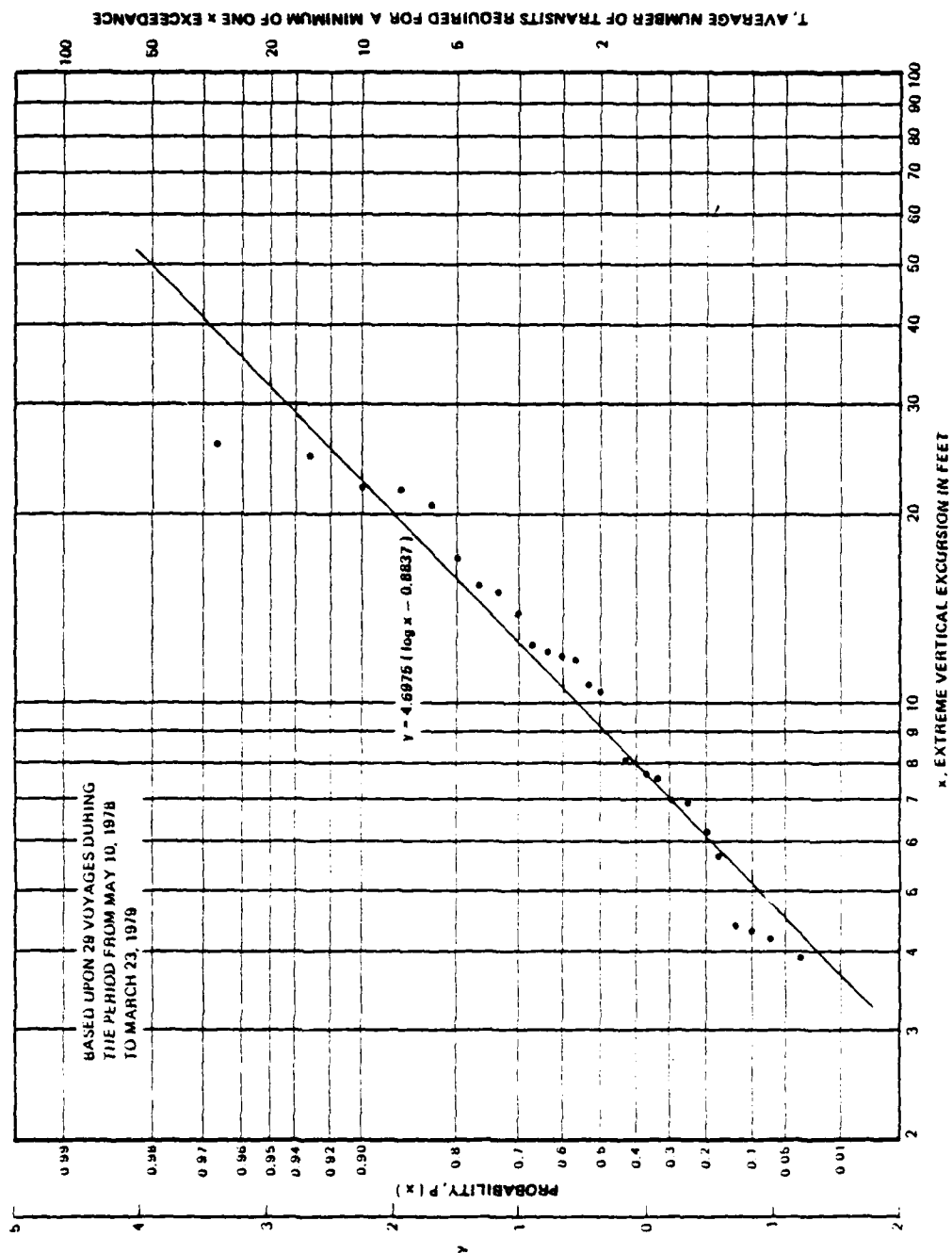


FIGURE 22 DISTRIBUTION OF THE EXTREME VALUES OF VERTICAL VESSEL EXCURSION (PHASE I DATA)

of the vertical vessel excursions can be fairly well represented by the distribution as described by Equation (23). Similarly, based on the Phase I data the extreme value distribution of vessel penetration is computed in Table 16 and plotted in Figure 23. Again, a good fit of the assumed distribution to the data is observed.

On the right side of Figures 22 and 23, a variable $T = 1/(1 - P)$ is introduced. This variable T denotes the average number of transits required in any one year period in order to exceed a particular value of the variate x .

Application of the same method to the total 51 recordings obtained from the 53 transits of the entire study is presented in Table 17 and the distribution to best fit these data is shown in Figure 24. The distribution fit for the Phase I data only is also included in this figure. Comparison of these two distribution functions indicates that there is no significant difference in large motions between these data. For instance, under the data bases of either the Phase I study or the study of Phases I and II combined, the result shows that there is a 90% probability that a given transit may experience up to a 22-23 ft vertical excursion. This is equivalent to saying that the probability to exceed a 22-23 ft vertical excursion is 10%; or, on the average, there is only one out of ten transits that may experience vertical excursions up to such a level.

The above discussion is based upon the assumption that the extreme value distribution for the data of interest follows the analytical form of equation (23). Indeed, through inspection, the assumed distribution fits fairly well to the measured data. In order to demonstrate more rigorously that the assumed form of distribution of extremes holds, however, confidence bands are determined with respect to the sample population to evaluate the degree of scatter that may be expected with the hypothesis. A 90% confidence limit curve is plotted

TABLE 16
COMPUTATION FOR FITTING A THEORETICAL EXTREME VALUE DISTRIBUTION
TO MEASURED DATA ON VESSEL PENETRATION
(PHASE I DATA)

MAXIMUM PENETRATION ft x	$\log_{10} x$ h	NUMBER OF OBSERVATIONS n	RANK m	P(x) $\frac{m}{N+1}$	$ h-\bar{h} $	$(h-\bar{h})^2$	VOYAGE NUMBER
29.3	1.4669	1	1	.033	.1335	.0178	3
31.3	1.4955	1	2	.067	.1049	.0118	4
32.5	1.5119	1	3	.1	.0885	.0078	17
33.1	1.5198	1	4	.133	.0806	.0065	11
33.3	1.5224	1	5	.167	.0780	.0061	6
33.7	1.5276	1	6	.2	.0728	.0053	12
33.8	1.5289	1	7	.233	.0715	.0051	24
34.0	1.5315	1	8	.267	.0689	.0048	26
35.9	1.5551	1	9	.3	.0453	.0021	7
36.1	1.5575	1	10	.333	.0429	.0018	27
36.6	1.5635	1	11	.367	.0369	.0014	20
37.6	1.5752	1	12	.4	.0252	.0006	25
37.7	1.5763	1	13	.433	.0241	.0006	18
38.3	1.5832	1	14	.467	.0172	.0003	28
38.5	1.5855	1	15	.5	.0149	.0002	29
40.2	1.6042	1	16	.533	.0038	0	22
40.3	1.6053	1	17	.567	.0049	0	13
40.7	1.6096	1	18	.6	.0092	.0001	23
40.9	1.6117	1	19	.633	.0113	.0001	9
41.1	1.6138	1	20	.667	.0134	.0002	21
43.8	1.6415	1	21	.7	.0411	.0017	2
46.3	1.6656	2	22, 49	.75	.0652	.0042	5, 14
48.2	1.6830	1	24	.8	.0826	.0068	10
49.5	1.6946	1	25	.833	.0942	.0089	1
51.2	1.7093	1	26	.867	.1089	.0119	15
53.1	1.7251	1	27	.9	.1247	.0155	8
53.9	1.7316	1	28	.933	.1312	.0172	16
56.3	1.7505	1	29	.967	.1501	.0225	19
$\Sigma = 46.4123$						$\Sigma = .1647$	

$N = 29$

Observed average:

$$\bar{x} = \frac{\Sigma x}{N} = 1.6004$$

Observed standard deviation:

$$s = \left[\frac{\Sigma (x - \bar{x})^2}{N-1} \right]^{1/2} = .0767$$

Expected average and standard deviation
of reduced variate y for a given N :

$$\bar{y}_N = 0.5353$$

$$\sigma_N = 1.1086$$

$$a = \frac{\Sigma N}{S} = 14.454$$

$$b = \bar{x} - \frac{\bar{y}_N}{a} = 1.5634$$

$$\text{Best fit: } y = 14.454(x - 1.5634)$$

*Reference [15]

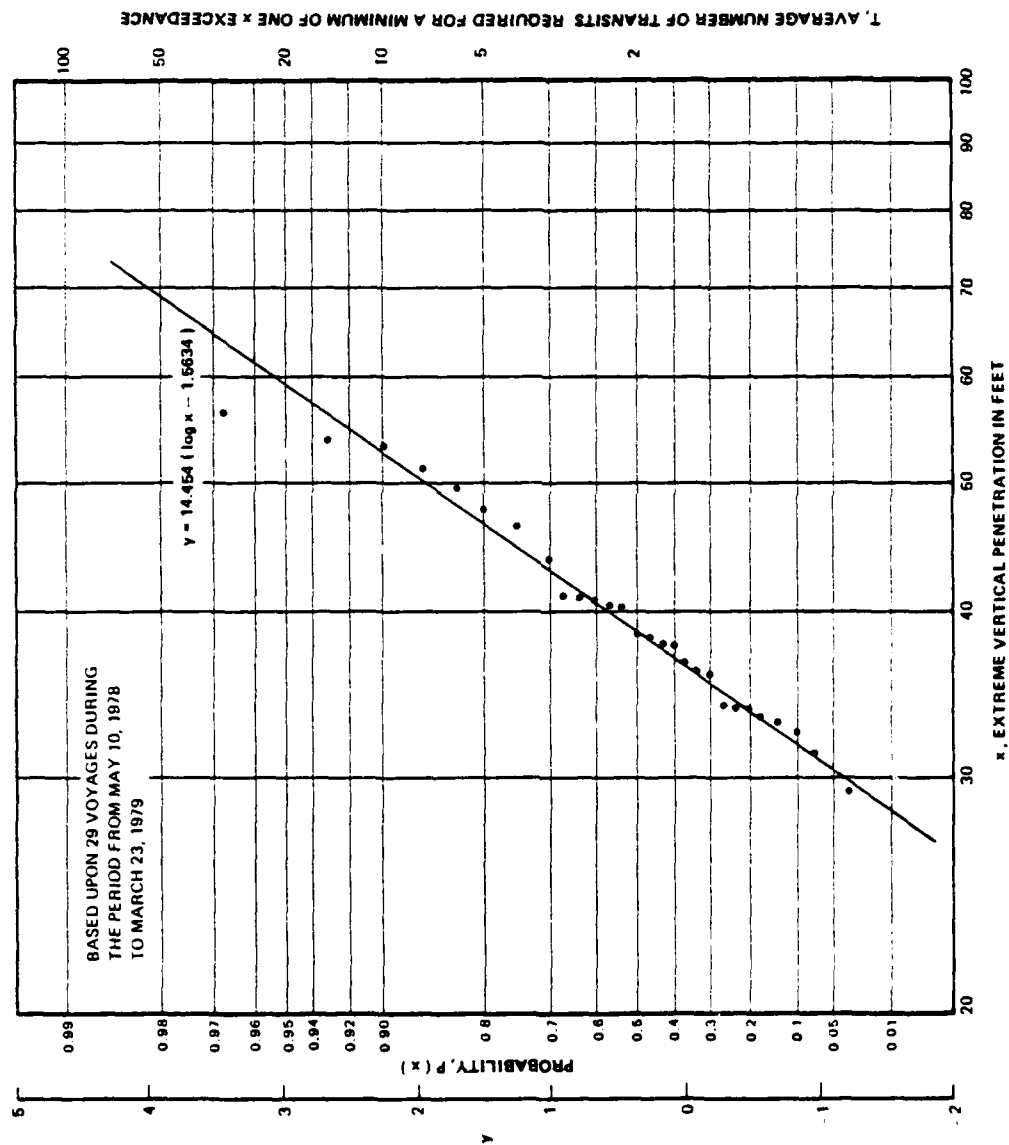


FIGURE 23 DISTRIBUTION OF THE EXTREME VALUES OF VESSEL PENETRATION (PHASE I DATA)

TABLE 17
COMPUTATION FOR FITTING A THEORETICAL EXTREME VALUE
DISTRIBUTION TO MEASURED DATA ON VERTICAL VESSEL EXCURSIONS
(PHASE I AND PHASE II DATA COMBINED)

EXTREME DOWNWARD EXCURSION ft x	$\log_{10} x$	NUMBER OF OBSERVATIONS n	RANK m	$P(x)$ $\frac{m}{N+1}$	$h-\bar{h}$	$(h-\bar{h})^2$	VOYAGE NUMBER
2.1	.3222	1	1	.019	.6191	.3833	39
2.4	.3802	1	2	.038	.5611	.3148	33
3.0	.4771	1	3	.058	.4642	.2155	53
3.5	.5441	1	4	.077	.3972	.1578	30
3.9	.5911	2	5.47	.105	.3502	.1226	26,37
4.1	.6128	1	7	.135	.3285	.1079	41
4.2	.6232	1	8	.154	.3181	.1012	17
4.3	.6335	2	9.49	.183	.3078	.0942	24,43
4.4	.6435	1	11	.212	.2978	.0887	25
4.7	.6721	1	12	.231	.2692	.0725	36
4.8	.6812	2	13.49	.259	.2601	.0677	42,45
5.7	.7559	1	15	.288	.1854	.0344	3
6.2	.7924	1	16	.308	.1489	.0222	12
6.3	.7993	1	17	.327	.1420	.0202	47
6.9	.8388	2	18.49	.356	.1025	.0105	13,27
7.0	.8451	1	20	.385	.0962	.0093	16
7.6	.8808	1	21	.404	.0605	.0037	20
7.7	.8865	1	22	.423	.0548	.0030	18
8.1	.9085	3	23.98	.461	.0328	.0011	4,7,23
9.0	.9542	1	26	.50	.0129	.0002	51
9.6	.9823	1	27	.519	.0410	.0017	46
10.1	1.0043	1	28	.538	.0630	.0040	32
10.4	1.0170	1	29	.558	.0757	.0057	2
10.6	1.0253	1	30	.577	.0840	.0071	11
11.7	1.0682	1	31	.596	.1269	.0161	22
11.8	1.0719	1	32	.615	.1306	.0171	5
12.0	1.0792	1	33	.635	.1379	.0190	28
12.3	1.0899	1	34	.654	.1486	.0221	21
13.5	1.1303	1	35	.673	.1390	.0357	34
13.9	1.1430	1	36	.692	.2017	.0407	9
14.0	1.1461	1	37	.712	.2048	.0419	35
14.4	1.1584	1	38	.731	.2171	.0471	46
15.0	1.1761	1	39	.750	.2348	.0551	10
15.2	1.1818	1	40	.769	.2405	.0578	29
15.8	1.1987	1	41	.788	.2574	.0663	40
16.6	1.2201	1	42	.806	.2788	.0777	44
17.0	1.2304	1	43	.827	.2891	.0836	1
18.1	1.2577	1	44	.846	.3164	.1001	52
18.5	1.2672	1	45	.865	.3259	.1062	50
20.3	1.3073	1	46	.885	.3662	.1341	8
21.9	1.3404	1	47	.904	.3991	.1593	15
22.0	1.3424	1	48	.923	.4011	.1609	14
22.9	1.3598	1	49	.942	.4185	.1751	31
24.3	1.3945	1	50	.953	.4051	.1651	19
25.7	1.4099	1	51	.968	.2196	.0479	16
$\Sigma = 48.0065$				$\Sigma = 3.9871$			

N = 51

Observed average:

$$\bar{h} = \frac{\Sigma h}{N} = .9413$$

Observed standard deviation:

$$s = \left[\frac{\Sigma (h-\bar{h})^2}{N-1} \right]^{1/2} = .2824$$

Expected average and standard deviation
of reduced variate y for a given N:

$$\bar{y}_N = 0.5489$$

$$s_N = 1.1623$$

$$a = \frac{s_N}{s} = 4.1158$$

$$b = \bar{h} - \frac{\bar{y}_N}{a} = .9079$$

Best fit: $y = 4.1158(h - .9079)$

*Reference [15]

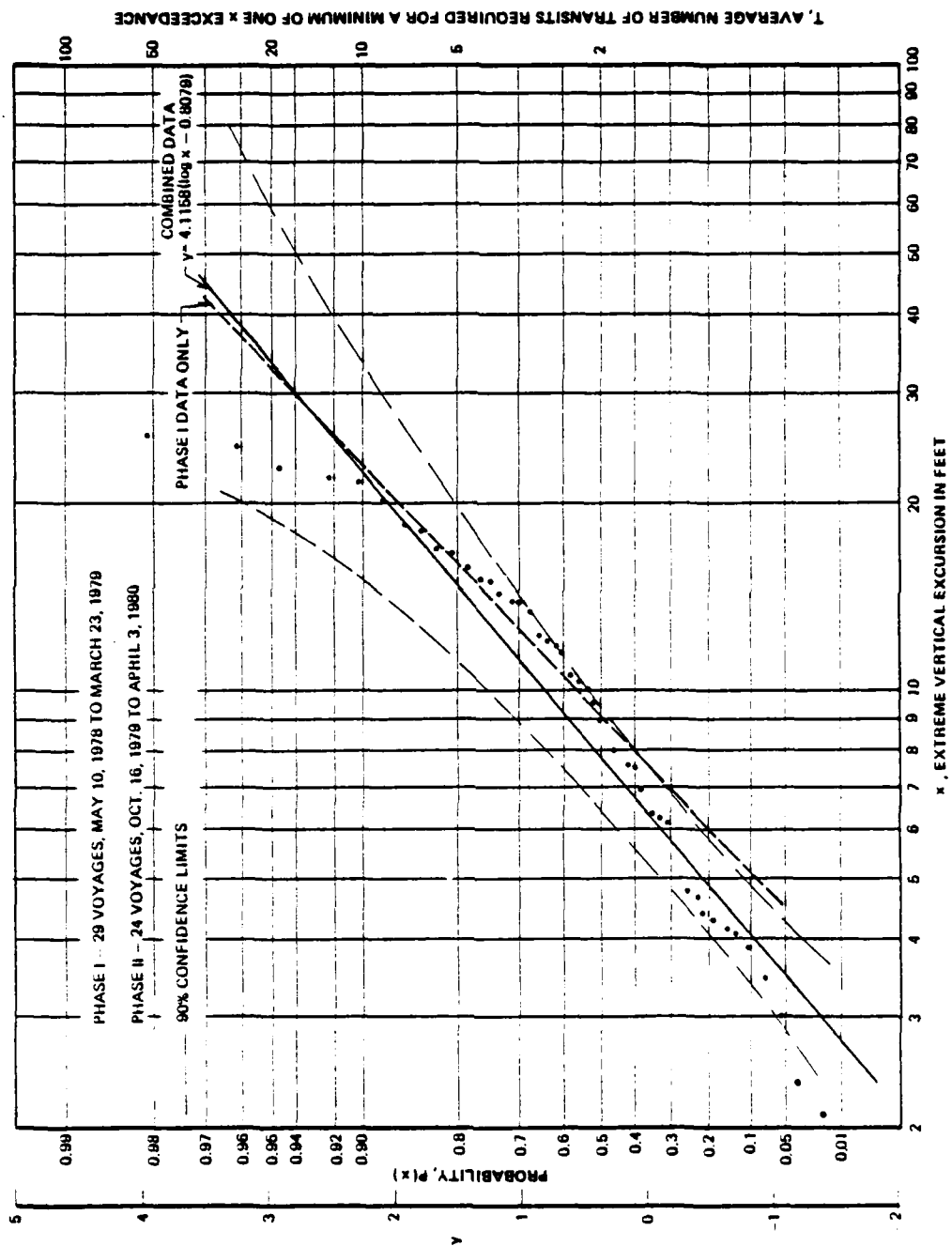


FIGURE 24 DISTRIBUTION OF THE EXTREME VALUES OF VERTICAL VESSEL EXCURSION (PHASE I AND II DATA)

on each side of the assumed distribution line as shown in Figure 24. Inasmuch as the scatter of the data lies well within these limits, the assumed form of distribution can be regarded as acceptable.

The combined data of the maximum penetration for Phase I and Phase II are analyzed and presented in Table 18 and Figure 25. On the average, the combined data indicate that the maximum penetration is slightly lower than that deduced from Phase I data. This is definitely the consequence of the differences exhibited in the two data bases due to the variation of ships, environments and many other minor factors. On the basis that the differences are small in both the underlying and the extreme value distributions, it is concluded that there is no significant difference between the Phase I and Phase II data, and the distributions derived from the combined data are probably representative for the project.

As also noted, the river entrance conditions were extremely mild during the Phase I study as evidenced by the number of bar closings during that period. Although the environmental conditions during the Phase II period were slightly more severe, based on the same evidence of bar closings, the motion response data obtained in Phase II are not as severe as those in Phase I as demonstrated in the foregoing. This is possible because the ships were randomly monitored on a convenient scheduling basis which had nothing to do with the weather conditions. Nevertheless, the statistical conclusions deduced from the measurements are probably credible even for relatively more severe seasons. Although the probability of exceedance for motions would increase during a severe season, neither the maximum motions would increase nor would the cumulative probability change significantly for the extremes. This is primarily due to the fact that bar closures limit the severity of environmental conditions that can be encountered. Thus the initial design criteria can be deduced from the existing data base even though it is based on mild winter conditions.

TABLE 18
COMPUTATION FOR FITTING A THEORETICAL EXTREME VALUE
DISTRIBUTION TO MEASURED DATA ON VESSEL PENETRATION
(PHASE I AND PHASE II DATA COMBINED)

MAXIMUM PENETRATION $\frac{F_t}{x}$	$\log_{10} x$	NUMBER OF OBSERVATIONS n	RANK m	$P(x)$ $\frac{m}{N+1}$	$h-\bar{h}$	$(h-\bar{h})^2$	VOYAGE NUMBER
26.5	1.4232	1	1	.0192	.1541	.0269	37
28.6	1.4564	1	2	.0385	.1309	.0171	43
29.3	1.4669	1	3	.0577	.1074	.0145	3
30.1	1.4786	1	4	.0769	.0887	.0118	33
31.3	1.4955	1	5	.0962	.0915	.0084	4
31.8	1.5024	1	6	.1154	.0849	.0072	47
32.4	1.5105	1	7	.1346	.0768	.0059	41
32.5	1.5119	1	8	.1538	.0754	.0057	17
33.1	1.5198	2	9, 10	.1730	.0675	.0046	11, 53
33.3	1.5224	1	11	.1922	.0649	.0042	6
33.7	1.5276	1	12	.2115	.0597	.0036	11
33.8	1.5289	1	13	.2307	.0584	.0034	24
34.0	1.5315	1	14	.2500	.0558	.0031	26
35.6	1.5514	1	15	.2692	.0359	.0013	42
35.8	1.5539	1	16	.2885	.0334	.0011	32
35.9	1.5551	1	17	.3077	.0322	.0010	7
36.0	1.5563	1	18	.3269	.0310	.0010	39
36.1	1.5575	1	19	.3462	.0298	.0009	27
36.3	1.5599	2	20, 21	.3650	.0274	.0008	30, 15
36.6	1.5635	1	22	.3846	.0238	.0006	20
37.3	1.5717	1	23	.4040	.0156	.0002	40
37.4	1.5729	1	24	.4233	.0144	.0002	26
37.6	1.5752	1	25	.4423	.0121	.0001	25
37.7	1.5763	1	26	.4615	.0110	.0001	19
38.3	1.5832	1	27	.4808	.0040	.0000	18
38.5	1.5855	1	28	.5000	.0013	.0000	29
38.9	1.5899	1	29	.5192	.0026	.0000	44
40.0	1.6021	1	30	.5385	.0148	.0002	46
40.2	1.6042	1	31	.5577	.0169	.0003	22
40.3	1.6053	1	32	.5769	.0180	.0003	13
40.5	1.6075	1	33	.5962	.0202	.0004	34
40.7	1.6096	1	34	.6154	.0223	.0005	23
40.9	1.6117	1	35	.6346	.0244	.0006	9
41.1	1.6138	1	36	.6538	.0265	.0007	21
42.2	1.6253	1	37	.6731	.0380	.0014	31
42.6	1.6294	1	38	.6922	.0420	.0018	48
43.0	1.6335	1	39	.7115	.0462	.0021	35
43.8	1.6415	1	40	.7308	.0542	.0029	2
44.3	1.6513	1	41	.7500	.0640	.0041	31
46.2	1.6656	2	42, 43	.7692	.0760	.0061	5, 14
48.0	1.6830	1	44	.7885	.0957	.0092	10
49.2	1.6920	1	45	.8077	.1047	.0110	30
49.5	1.6946	1	46	.8269	.1073	.0115	1
49.8	1.6972	1	47	.8462	.1099	.0121	30
51.2	1.7093	1	48	.8654	.1220	.0149	16
53.1	1.7251	1	49	.8846	.1378	.0190	8
53.9	1.7316	1	50	.9038	.1443	.0209	18
56.3	1.7505	1	51	.9231	.1632	.0266	19

$\bar{h} = 30.9505$

$\bar{h} = 30.9510$

$N = 51$

Expected average and standard deviation
of reduced variate y for a given N :

Observed average:

$$\bar{y}_N = 0.5489$$

$$\bar{h} = \frac{\sum h}{N} = 1.5873$$

$$\sigma_N = 1.1623$$

Observed standard deviation:

$$s = \sqrt{\frac{\sum (h - \bar{h})^2}{N-1}} = .0750$$

$$A = \frac{\sigma_N}{s} = 15.4973$$

$$b = \bar{h} - \frac{\bar{y}_N}{A} = 1.5519$$

Best fit: $y = 15.4973(h - 1.5519)$

*Reference [15]

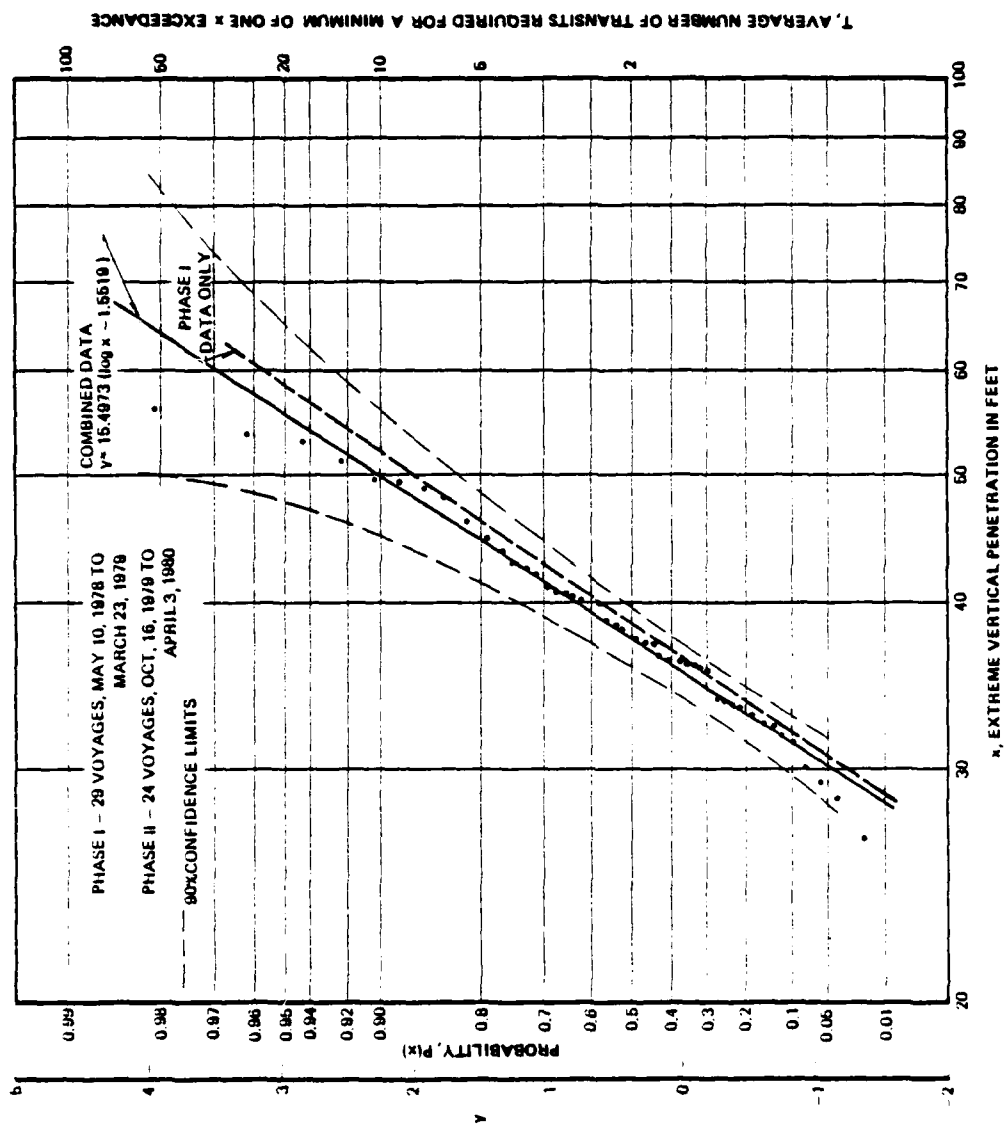


FIGURE 25 DISTRIBUTION OF THE EXTREME VALUES OF VESSEL PENETRATION (PHASE I AND II DATA)

8.0 HORIZONTAL SHIP EXCURSIONS

8.1 VESSEL TRACKS

The ship track plots for all the voyages except Nos. 3, 8, 14, 25, 41, 45 and 49 are given in Appendix A. For those voyages listed above, the vessel tracks were unobtainable due to the failure of one of the several components of the positioning system. While the individual track plots are given in the appendix, a superimposition of these tracks is plotted and displayed in Figures 26 and 27, in order to show the actual coverage of these tracks over the entrance channel. Figure 26a shows the 18 recorded inbound trips in the Phase I study and Figure 26b completes the picture with the 7 recorded outbound voyages for the Phase I study. Similarly, Figures 27a and 27b correspond to the inbound and outbound voyages for the Phase II study.

Inspecting the inbound trajectories of both Phase I and II, all but a few exceptions are distributed within a narrow band around the centerline of the channel. As soon as the ships are inside the jetties, however, they tend to stay in the starboard side lane as Figures 26a and 27a show. The spread of these tracks for Phase I and Phase II is about 40% and 60%, respectively, of the current channel width.

The nine exceptions are Phase I Voyage Nos. 6, 12, 23, 24, and 26 and Phase II Voyages Nos. 32, 33, 36, and 37. Checking the log of our field study indicates that all the ships in these voyages, except Voyage No. 33, were approaching the channel from the north and consequently the ship tracks originate well to the north of the centerline. If, however, outbound traffic had been present during these transits, the inbound vessel undoubtedly would have approached the buoyed channel from south of the centerline. The deviation of Voyage No. 33 is attributed to the passage of a small boat heading south across the channel in front of the ship.

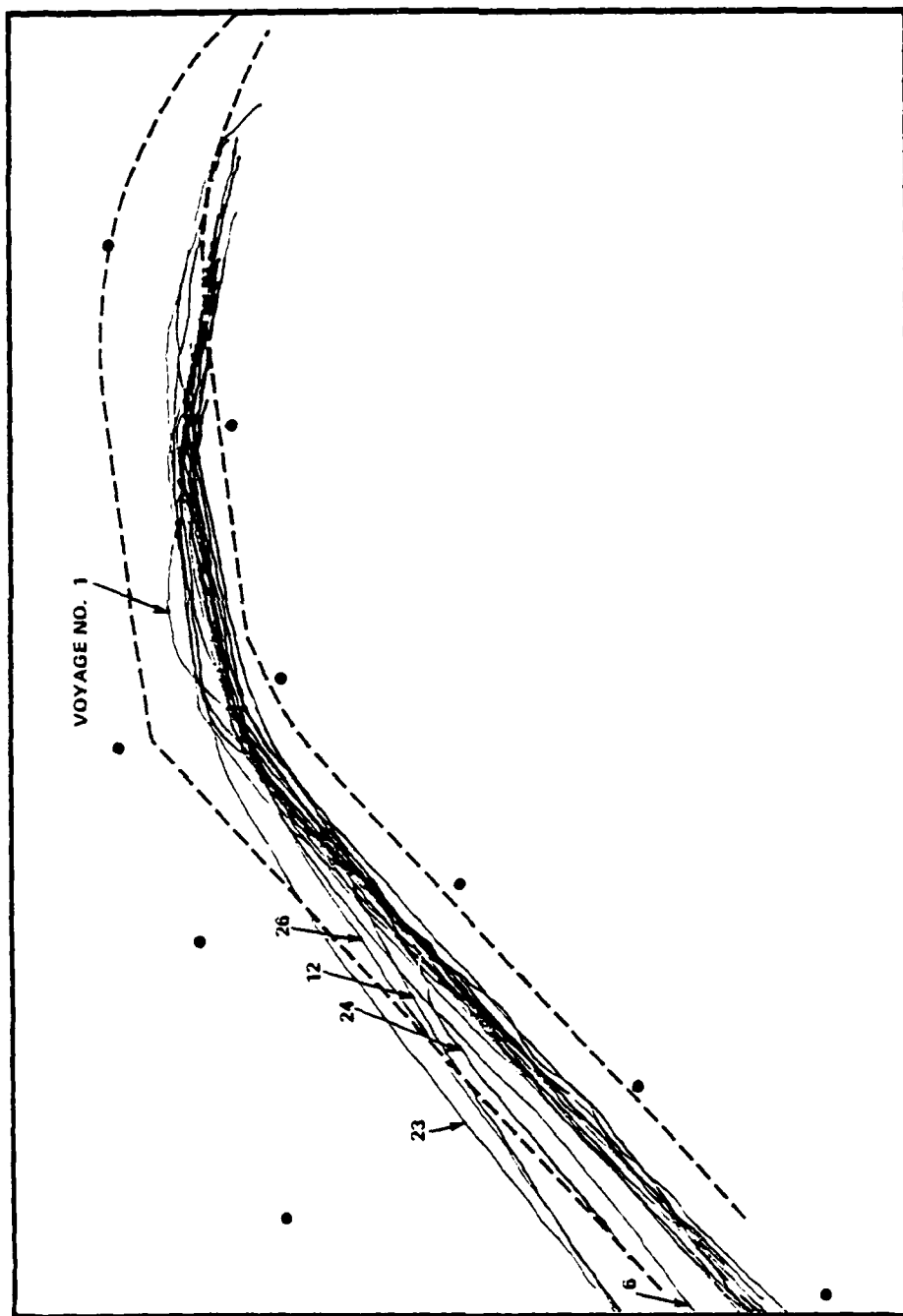


FIGURE 26a VESSEL TRACKS OF INBOUND VOYAGES (PHASE I)

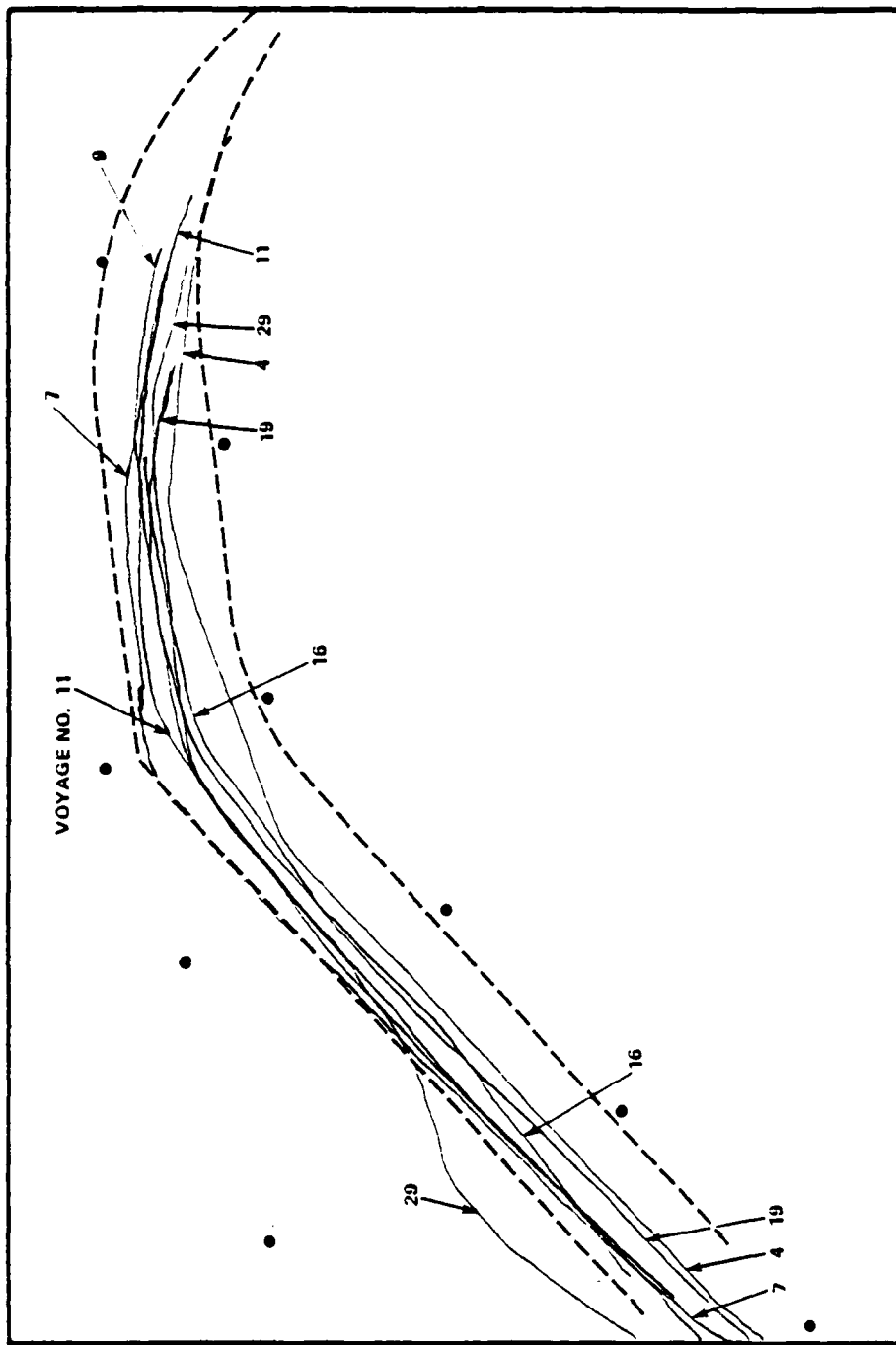


FIGURE 26b VESSEL TRACKS OF OUTBOUND VOYAGES (PHASE I)

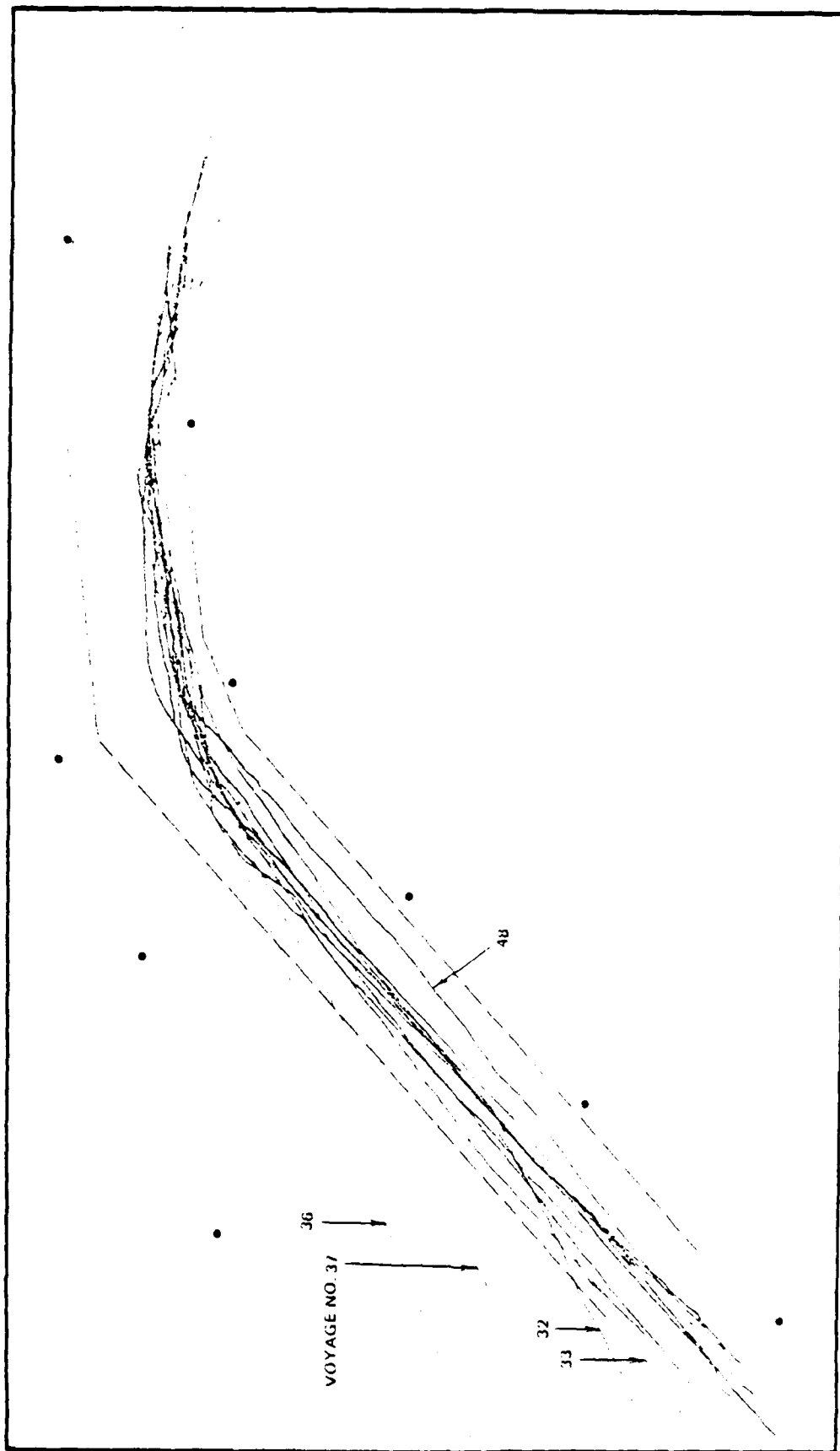


FIGURE 27 • VESSEL TRACKS OF INBOUND VOYAGES (PHASE II)

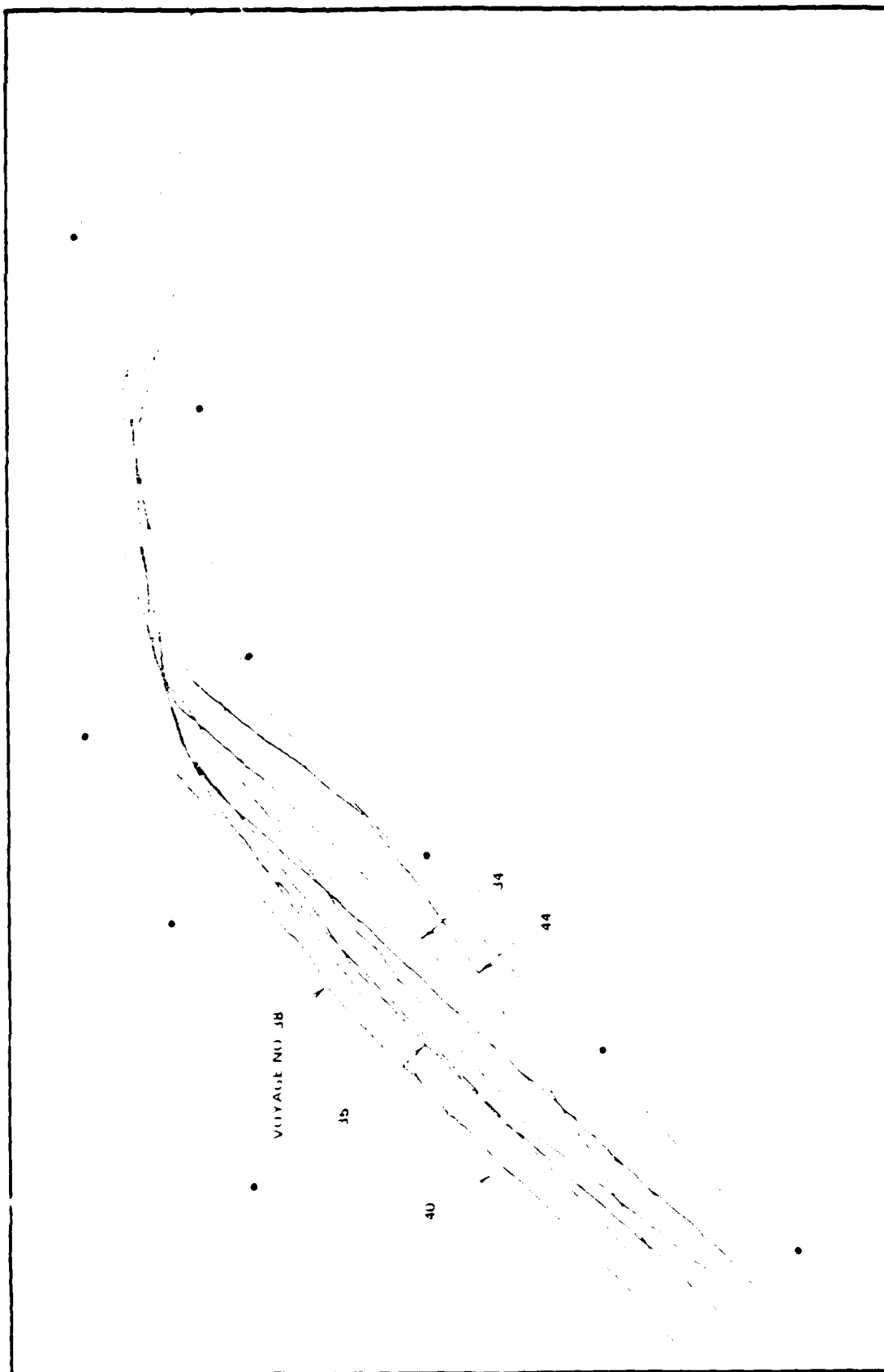


FIGURE 27b VESSEL TRACKS OF OUTBOUND VOYAGES (PHASE II)

The plots of the Phase I outbound tracks (Figure 26b) show that most ships tend to stay on the starboard side lane of the channel, both inside and outside the jetties (Sand Island Range and Entrance Range, respectively). The deviation of Voyage No. 29 from the others is attributable to the passage of two inbound vessels at the channel entrance. The appreciably large deviation from the channel alignment is probably due to the heavy fog condition which prevailed. A precautionary maneuver of this nature is made possible in the outermost portion of the channel by the presence of deep water north of the authorized channel section (Ref. Figure 1).

The plot of Phase II outbound tracks (Figure 27b) shows that again most ships started from the starboard side lane. However, five vessels, Voyage Nos. 34, 35, 38, 40, and 44, deviated from the starboard side lane. The deviation of Voyage Nos. 35 and 38 was caused by a combination of strong ebb currents and 35-40 knot southeasterly winds which forced these vessels north and off of the channel range. Conversely, the deviation on Voyage Nos. 34 and 44 was caused by strong flood currents and 35-40 knot westerly winds which forced these vessels into the port side lane. The deviation of Voyage No. 40 can be attributed to another outbound vessel overtaking on the port side causing the ship in Voyage No. 40 to stay to the north of the authorized channel.

The purpose of superimposing these ship tracks is to indicate how the existing navigation lanes are currently utilized. The resulting plots are of limited utility in assessing an optimum channel width and alignment, since there was no specific constraint on vessel tracks applied to the vessels during the measured transits.

8.2 YAW AND SIDEWAYS EXCURSIONS

As previously mentioned, the total sideways excursion is a

combination of the oscillatory yaw motion and the sway. Instead of measuring yaw and sway directly, the present Ship Motion and Positioning System (SMPS) records the ship heading and position as a function of time, from which computations must be made in order to determine the sideways excursion. As shown by the sketch in Figure 28, the horizontal motions are characterized by two major components, the path deviation from the vessel's intended course (hereafter referred to as "course made good") and the yaw oscillation about the deviated path. The total sideways excursion or effective lane width that the ship requires is therefore defined as the combination of the ship track width and one-half of the ship's cross-channel projection caused by the yaw deviation on each side of the track. A sample of the ship track plot as drawn from the positioning data for Voyage No. 9 has already been presented and discussed in Section 7.1, Figure 12. A sample of the ship's heading data for Voyage No. 9, which is presented in Figure 29, clearly shows the long period (approximately one minute) heading oscillations corresponding to path deviation from the course made good, and the short period yaw oscillations about the deviated path. In addition, the ship heading plot clearly shows the course changes made throughout the transit. Referring to the heading plot and the ship track plot it is seen that at about minute 2, a course change was made from 280° to 258° and the ship remained on that course between buoy Nos. 10 and 8 in the Sand Island Range. Then from minute 7 to 13 a gradual course change was made from 258° to bring the ship onto the Entrance Range.

The method of processing yaw oscillation about the ship's path by means of computer analysis has been discussed in Section 6.2. Determination of the track width, however, is more conveniently done by inspection rather than computer analysis. In general, the ship track width is scaled off of the ship track plot. On each ship track plot, a straight-line course is first determined. This course corresponds to that portion

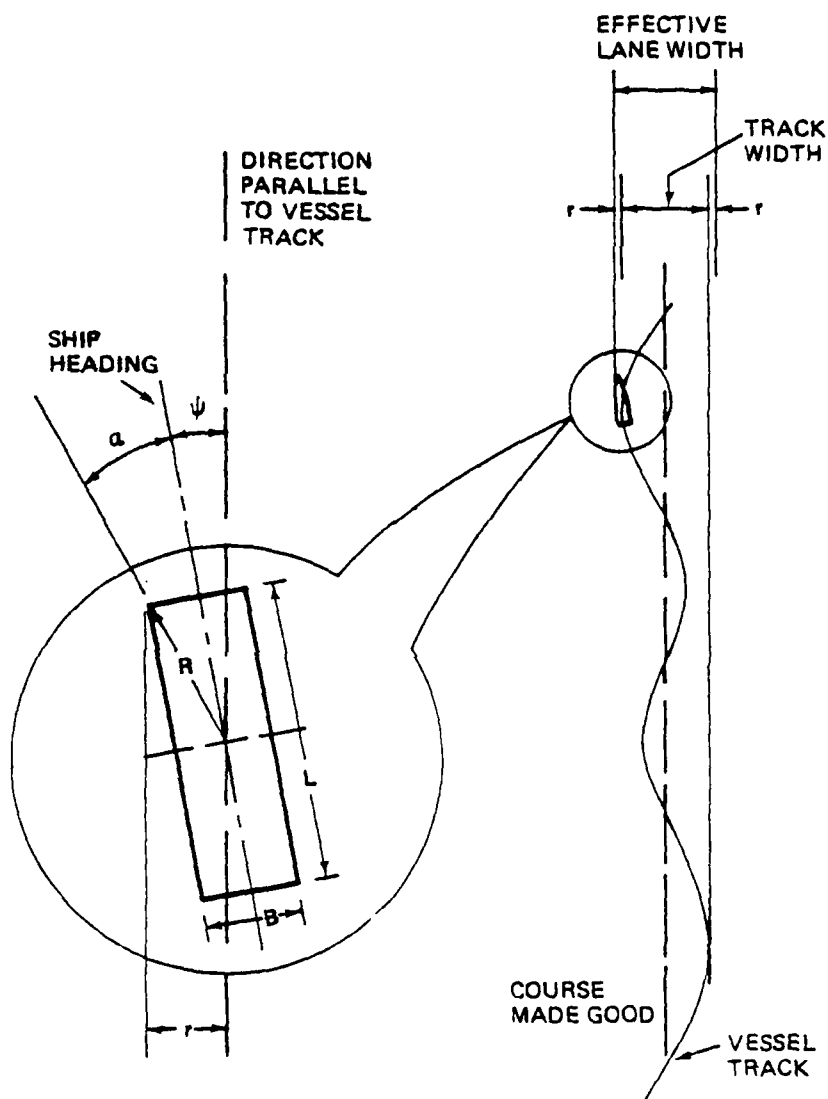


FIGURE 28 — SKETCH SHOWING THE EFFECTIVE LANE WIDTH

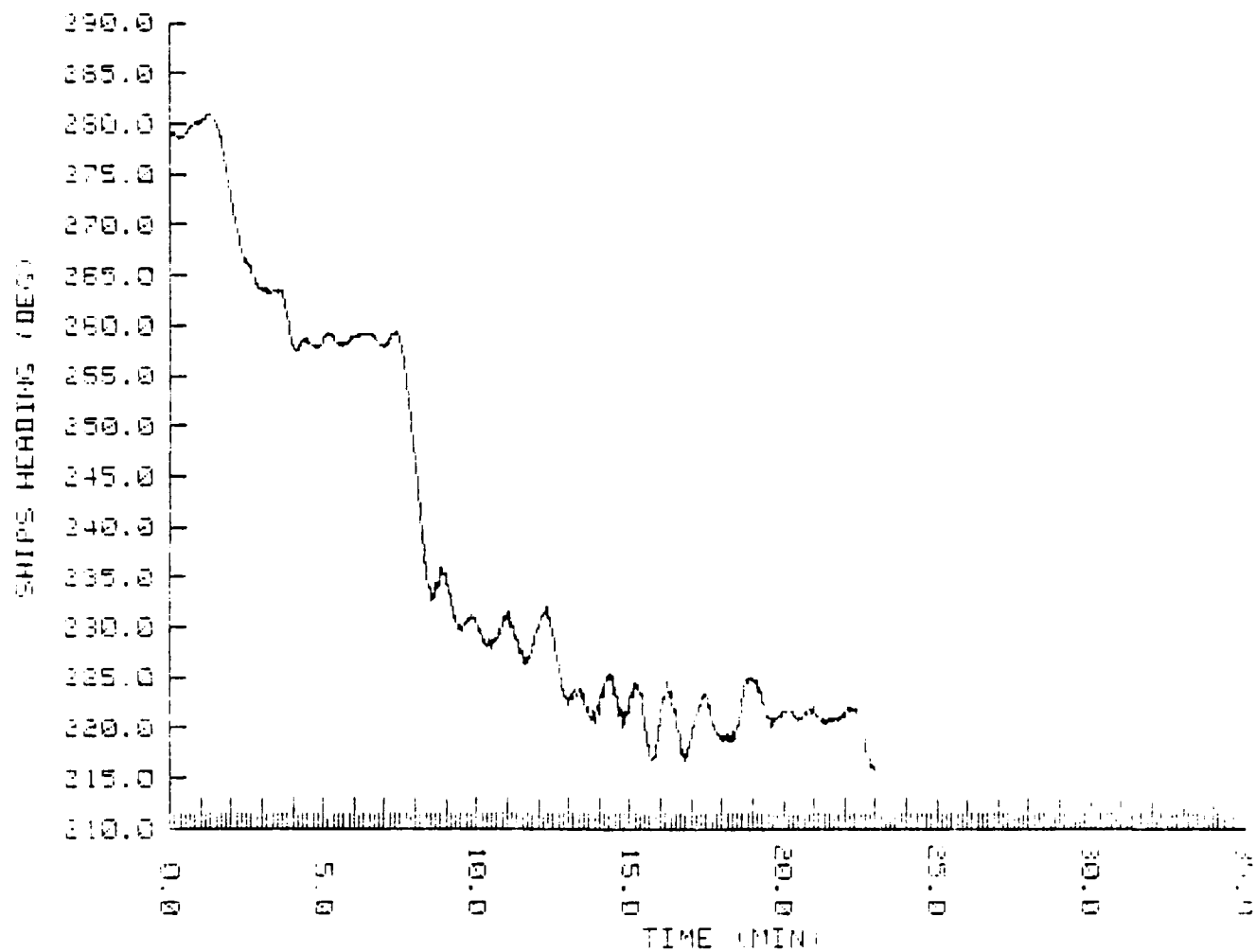


FIGURE 29 - SAMPLE OF SHIP'S HEADING PLOT (VOYAGE NO. 9)

of the track for which the ship holds a steady course and is defined as the course made good. The track width then is the cross-sectional span that encompasses the maximum port and starboard deviations from the course made good.

By assuming the ship to be a rectangular box of length L and beam B , the additional projection r , due to a yaw angle ψ is given by (Ref. Figure 28):

$$r = R \sin (\alpha + \psi) \quad (24)$$

where $R = [L^2 + B^2]^{\frac{1}{2}} / 2$
 $\alpha = \tan^{-1}(B/L)$

In determining the effective lane width, the maximum recorded yaw angle was used. The computer-processed yaw angles (average and maximum), the measured track widths and the effective lane widths for the recorded voyages are given in Table 19.

As shown in Table 19a of the Phase I data, the ship track width, W , varies from 140 ft (Voyage No. 17) to 620 ft (Voyage No. 15). The contribution due to yaw deviation, $2r$, ranges from 91 ft (Voyage No. 18) to 160 ft (Voyage No. 15). Voyage No. 15 represents the roughest conditions among the 29 Voyages of Phase I. Whereas the yaw angle and the path deviation are both significantly larger than those of other voyages, the ratio of the yaw contribution to the path deviation, $2r/W$, for this particular transit is 26%, which is considerably lower than that for most of the other, easier transits. The effect of ship yaw on the lane width requirement, therefore, seems less significant in a relatively rough transit than in an easier transit, as the predominant parameter here is the track width, W .

The variation of the ship track width, W , as well as the contribution due to yaw deviation, $2r$, is on the same order of magnitude in the Phase II data as shown in Table 19b, except

TABLE 19a
DATA ON YAW MOTION AND SIDEWAYS EXCURSION
(PHASE I)

VOYAGE NUMBER	COURSE MADE (DEG)	TRACK WIDTH W (FT)	YAW OSCILLATIONS		PROJECTION DUE TO YAW $2r$ (FT)	EFFECTIVE LANE WIDTH $W + 2r$ (FT)	EFFECTIVE LANE WIDTH IN TERMS OF SHIP BEAM $(W + 2r)/B$	RATIO OF $2r/W$
			AVE (DEG)	MAX (DEG)				
1	45.5	490	-	-	-	-	-	-
2	44.1	150	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	41.7	150	-	-	-	-	-	-
5	46.2	180	-	-	-	-	-	-
6	48.0	480	-	-	-	-	-	-
7	221.6	270	-	-	-	-	-	-
8	-	-	1.6	4.8	150	-	-	-
9	222.9	200	0.2	0.7	104	304	3.16	0.52
10	42.4	290	0.2	0.7	104	394	4.10	0.36
11	225.9	150	0.1	0.3	99	249	2.59	0.66
12	54.9	460	0.1	0.4	103	563	5.72	0.22
13	42.9	220	0.4	2.1	119	339	3.54	0.54
14	-	-	0.5	4.1	142	-	-	-
15	44.2	620	4.0	10.3	161	781	11.48	0.26
16	226.9	600	1.2	4.5	109	709	10.43	0.18
17	46.9	275	0.5	2.0	122	397	4.01	0.45
18	43.4	200	0.4	1.8	91	291	4.07	0.46
19	223.9	300	0.9	3.1	106	406	5.67	0.35
20	43.9	200	0.8	2.6	133	333	3.28	0.67
21	45.1	320	1.5	4.3	129	449	5.43	0.40
22	44.4	410	1.0	4.0	146	556	5.64	0.36
23	49.9	200	0.7	4.2	155	355	1.46	0.77
24	55.8	180	0.3	2.0	123	303	1.07	0.68
25	-	-	0.1	1.4	98	-	-	-
26	52.0	200	0.1	0.5	104	304	3.09	0.52
27	44.7	140	0.4	2.7	131	271	2.75	0.94
28	45.9	200	0.7	3.2	132	332	1.46	0.66
29	-	200	0.1	0.5	101	301	1.14	0.51

Indicates data unavailable
 Voyages 3, 8, 14 and 25 - Mini Ranger failures
 Voyages 17 - Heading sensor failures
 Voyage 29 - Excessive course deviation due to opposing traffic

TABLE 19b
DATA ON YAW MOTION AND SIDEWAYS EXCURSION
(PHASE II)

VOYAGE NUMBER	COURSE MADE GOOD (DEG)	TRACK WIDTH W (FT)	YAW OSCILLATIONS		PROJECTION DUE TO YAW 2r (FT)	EFFECTIVE LANE WIDTH W + 2r (FT)	EFFECTIVE LANE WIDTH IN TERMS OF SHIP BEAM (W + 2r)/B	RATIO OF 2r/W
			AVE (DEG)	MAX (DEG)				
30	43.6	140	0.1	0.3	99	239	2.49	0.71
31	226.7	400	0.2	0.5	102	502	5.23	0.25
32	49.7	360	1.1	3.3	138	498	5.06	0.38
33	52.8	143	0.1	0.2	103	246	2.44	0.72
34	222.6	288	0.3	0.8	110	398	2.85	0.38
35	225.0	503	0.2	0.9	81	584	8.17	0.16
36	68.6	288	0.2	0.8	91	379	4.58	0.32
37	57.1	143	0.2	0.8	110	253	2.50	0.77
38	223.8	206	0.1	0.4	106	311	3.08	0.51
39	44.9	214	0.3	5.9	162	376	3.92	0.79
40	231.5	320	0.2	0.9	106	426	4.44	0.33
41	-	-	0.1	0.3	-	-	-	-
42	44.5	357	0.4	1.9	103	460	5.56	0.29
43	50.7	200	0.1	0.6	96	296	3.27	0.48
44	230.5	1218	0.3	3.5	125	1343	14.82	0.10
45	-	-	0.3	1.6	-	-	-	-
46	221.3	191	0.8	0.2	110	301	2.98	0.58
47	45.4	216	0.1	0.4	76	292	4.09	0.35
48	47.0	324	0.1	0.3	106	431	4.20	0.33
49	-	-	-	-	-	-	-	-
50	225.0	357	0.1	0.5	107	464	4.59	0.37
51	44.7	143	1.0	2.9	114	257	3.10	0.80
52	42.3	286	0.9	4.3	150	436	4.42	0.52
53	49.6	286	0.4	1.8	122	408	4.03	0.43

- indicates data unavailable
Voyages 41 and 45 - Mini Ranger failure
Voyage 40 - Data processor failure

for the case of Voyage No. 44, where the effective lane width is approximately twice as wide as the next largest one (Voyage No. 15). The exceptional transit of Voyage No. 44 was due to two major factors: 1) rough environmental conditions of winds and waves, and 2) large sail area of the auto-carrier *World Wing*. The ship track plot for this particular transit is shown in Figure 30. In order to show the chronological sequence during the maneuver, the data log for this particular transit is included in the following:

Voyage No. 44 - *World Wing* - Outbound
6 February 1980
Data recording from 1333-1409 hours

The bar has been closed since 0600 this morning and we will be the first ship out since the bar has reopened. Wind speed is 25-30 knots from the east, gusting to 40 knots. The pilot reports that it is very rough outside with high winds and heavy swell. The tide is flooding and is midway between slack and high water (weak current).

- 1311 - Winds are picking up, still gusting to 40 knots.
- 1322 - The pilot boat *Peacock*, which is outside the bar, radios that the swell is short, sharp and 10-15 ft with slight slop.
- 1333 - We are now abeam buoy No. 12 and the data recording is started. The pilot says we are being set to the right of the channel and we have about a 5° leeway.
- 1345 - Abeam buoy No. 8.
- 1349 - Abeam buoy No. 6, still 5° leeway.
- 1351 - 10° leeway.
- 1356 - 15° leeway. The pilot just commented that steerage is difficult in the strong winds, because the *World Wing*, an auto carrier, has a large sail area.
- 1402 - Abeam buoy No. 4.
- 1406 - Slowing to allow an incoming ship to be worked by the pilot boat. We will stay to the starboard side of the channel.
- 1409 - End of data recording.

The crossing was rated moderate by the pilot, but he thought it notable that no reduction from sea speed was necessary. Visibility was reduced considerably from the beginning of the recording till about buoy No. 6, then increased from there to buoy No. 2. Winds remained easterly but abated somewhat to about 20-25 knots, gusting to 30 knots. Swell unchanged, westerly, 10-15 ft and short.

During the Phase II measurements, it was hoped that the strip chart recordings of rudder deflections could be obtained.

VOYAGE NO. 44 SHIP TRACK
SCALE 1: 30000

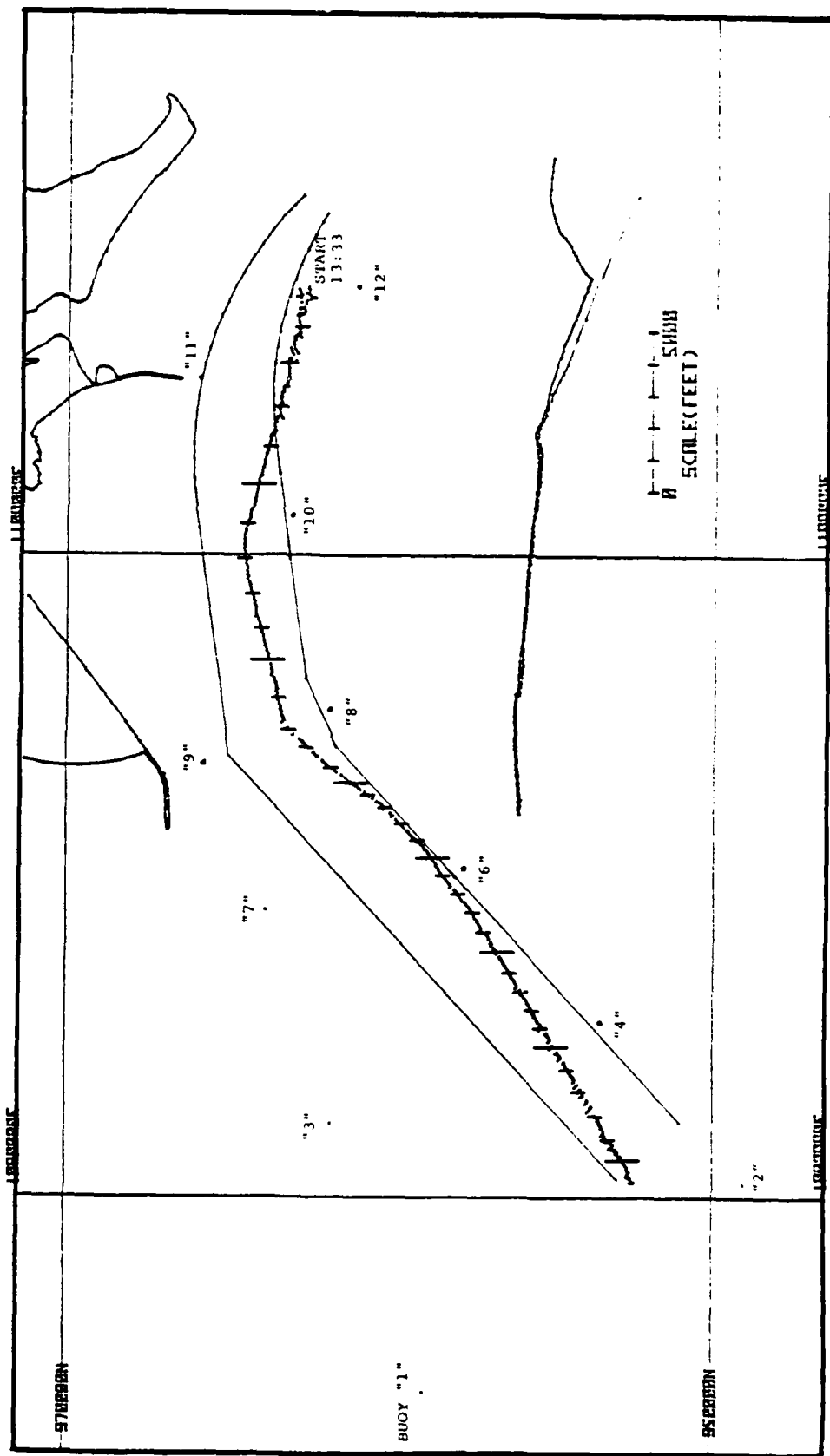
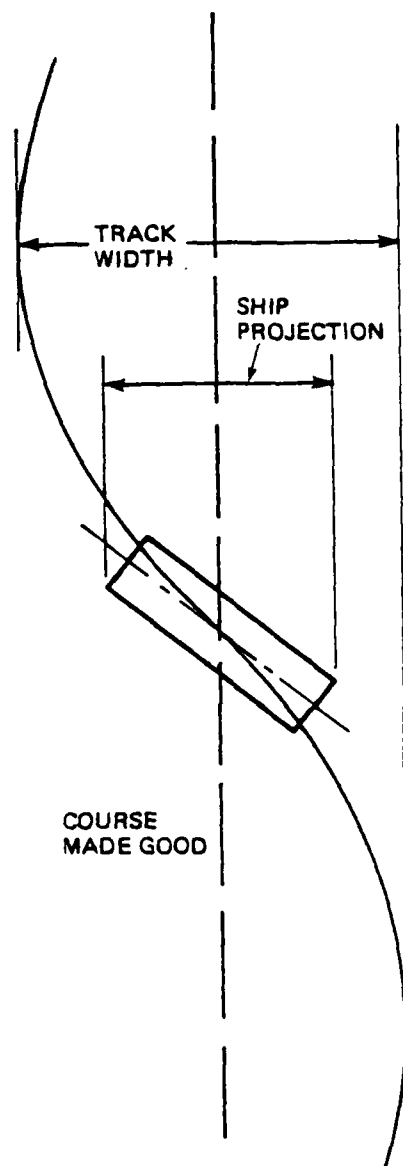


FIGURE 30 SHIP TRAJECTORY PLOT FOR VOYAGE NO. 44

Unfortunately, they were obtainable on only two voyages aboard the *Chevron Arizona*. The actual recordings are included in Appendix J.

The summation of the track width together with the yaw contribution gives the effective lane width, which is regarded as the reference value for determining the lane width requirement. In terms of ship beam, the non-dimensional values of the effective lane width are also presented in Table 19. Based upon the 40 sets of available data, it is seen that the maximum width recorded during the entire season is on the order of 15 times the breadth of the ship. The average value of the effective lane width is 413 ft, with a standard deviation of 195 ft. For a 90% safety, each maneuvering lane seems to require a width of 735 ft.

Besides the values of yaw oscillation about the mean vessel track (Figure 28), another parameter of interest is the maximum angular deviation of the ship's track from the course made good (Figure 31). This value usually is significantly larger than the ship yaw displacement, but the projection width due to the angular deviation normally is not as large as the curvi-linear path deviation or track width. Values of the angular deviation and the width projection due to this angle are summarized in Table 20.



**FIGURE 31 – SKETCH SHOWING SHIP PROJECTION WIDTH
DUE TO MAXIMUM HEADING DEVIATION**

TABLE 20a MAXIMUM HEADING DEVIATION FROM COURSE MADE GOOD
(PHASE I)

VOYAGE NUMBER	COURSE MADE GOOD (DEG)	DEVIATION ANGLE (DEG)	CROSS CHANNEL PROJECTION (FT)	CROSS CHANNEL PROJECTION SHIP BEAM
1	45.5	-	-	-
2	44.1	-	-	-
3	-	-	-	-
4	43.7	-	-	-
5	46.2	-	-	-
6	48.0	-	-	-
7	221.6	-	-	-
8	-	-	-	-
9	222.9	6.7	171	1.78
10	42.4	10.0	208	2.16
11	225.9	7.0	175	1.82
12	54.9	9.0	205	2.08
13	42.9	7.5	180	1.88
14	-	-	-	-
15	44.2	36.8	368	5.41
16	226.9	10.6	163	2.40
17	46.9	4.6	153	1.55
18	43.4	6.0	137	1.92
19	223.9	6.0	172	2.41
20	43.9	5.5	168	1.66
21	45.1	9.7	185	2.24
22	44.4	6.8	179	1.82
23	49.9	5.0	165	1.61
24	55.8	6.2	173	1.76
25	-	-	-	-
26	52.0	4.0	146	1.48
27	44.7	3.0	135	1.37
28	45.9	9.4	201	2.09
29	-	-	-	-

- indicates data unavailable
 Voyages 3, 8, 14 and 25 - Mini-Ranger failures
 Voyages 1-7 - Heading sensor failures
 Voyage 29 - Excessive course deviation due to
 opposing traffic

TABLE 20b MAXIMUM HEADING DEVIATION FROM COURSE MADE GOOD
(PHASE II)

VOYAGE NUMBER	COURSE MADE GOOD (DEG)	DEVIATION ANGLE (DEG)	CROSS CHANNEL PROJECTION (FT)	CROSS CHANNEL PROJECTION SHIP BEAM
30	43.6	2.0	119	1.24
31	226.7	8.0	186	1.93
32	46.4	5.0	158	1.60
33	52.8	2.0	124	1.23
34	222.6	4.0	147	1.45
35	225.0	14.0	222	3.10
36	68.6	5.5	141	1.71
37	57.1	6.0	169	1.68
38	223.8	17.0	289	2.86
39	44.9	5.0	152	1.59
40	231.5	4.0	141	1.47
41	-	-	-	-
42	44.5	4.0	126	1.57
43	50.7	3.0	120	1.33
44	230.5	11.0	197	2.18
45	-	-	-	-
46	221.3	5.0	158	1.56
47	45.4	5.0	126	1.77
48	47.0	5.0	165	1.61
49	-	-	-	-
50	225.0	6.0	166	1.65
51	44.7	11.0	199	2.41
52	42.3	8.5	199	2.02
53	49.6	4.5	152	1.51

- indicates data unavailable
 Voyages 41 and 45 - Mini-Ranger failures
 Voyage 49 - Data processor failure

9.0 SPECTRA ESTIMATES

9.1 SHIP MOTION SPECTRA

Pitch, roll and vertical bow motion spectra were computed for each transit of the second phase study, together with several selected transits of the first phase study for which the measured wave data were available. These spectra were computed through the Fast Fourier Transform (FFT) procedure [16]. Owing to the limited memory space of the HP9845 desktop computer, a maximum of 256 data points was used for each data segment. With the time interval Δt of 1 second selected for the process, each segment of data covers approximately a transit distance between two adjacent buoys in the channel. Consequently, three segments of data corresponding to transits from buoy Nos. 2 to 4, 4 to 6, and 6 to 8 are processed for each voyage. Finally a segment averaging procedure [17] was applied to the results of the three segments of data to obtain the spectra estimates representing the entire transit between buoy Nos. 2 and 8. As a typical example, a complete set of the motion spectra for Voyage No. 31 is shown in Figures 32, 33, and 34. From each of these figures, the spectral distributions along the channel segments can be compared and the validity of whether the average spectra is representative for the entire transit can be justified. To summarize the results for all the voyages processed in this study, the average amplitude, the average period, and the peak period are tabulated and presented in Table 21. Plots of the computed spectra representing the entire transit between buoy Nos. 2 and 8 are presented in Appendix K.

During the second phase of the study, the periods of pitch and roll responses were recorded using the simple stopwatch timing technique. The peak spectral periods and the average periods processed between buoy Nos. 2 and 8 are compared with the observed values and are shown in Table 22. The average period

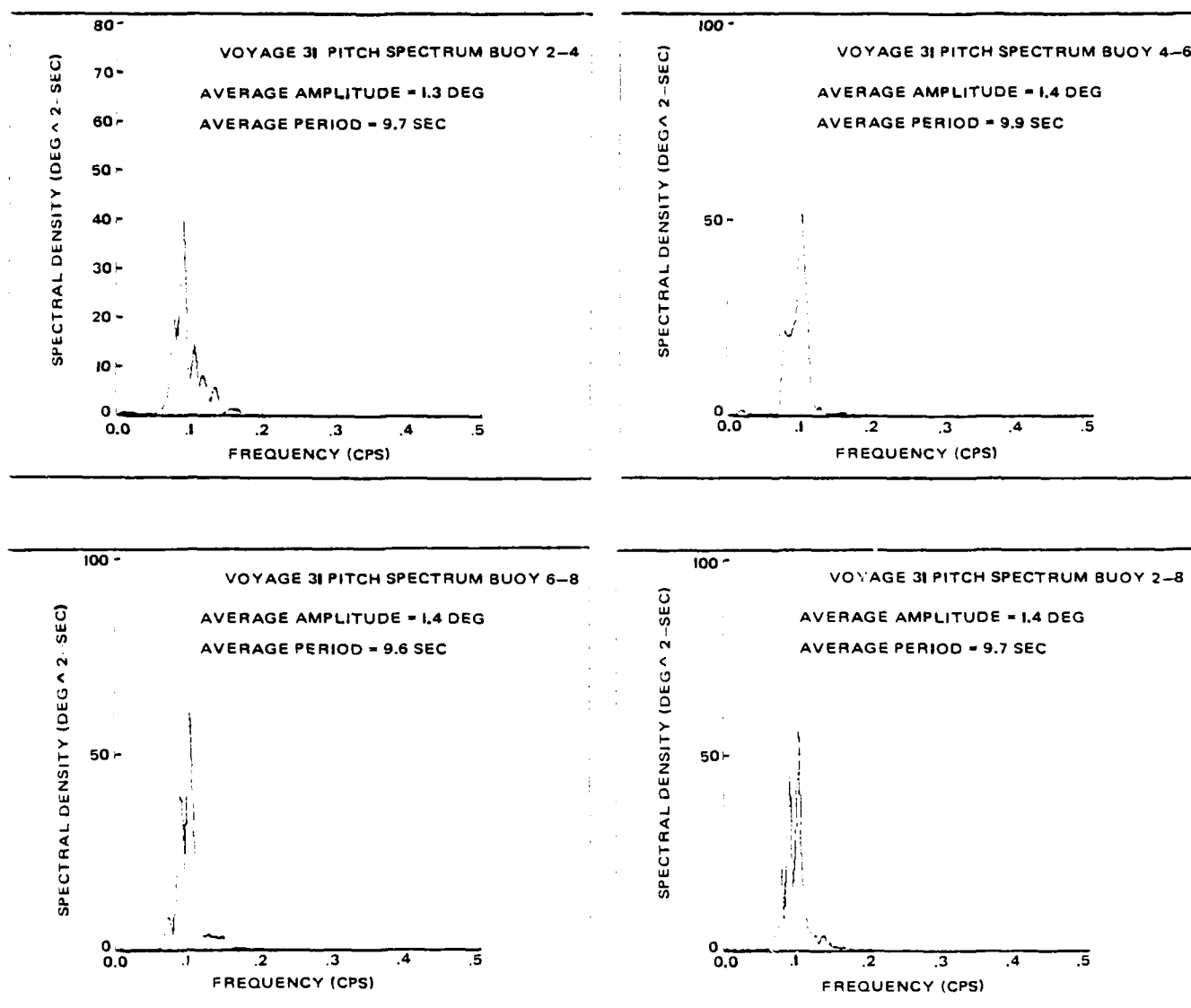


FIGURE 32 PITCH SPECTRA FOR VOYAGE NO. 31

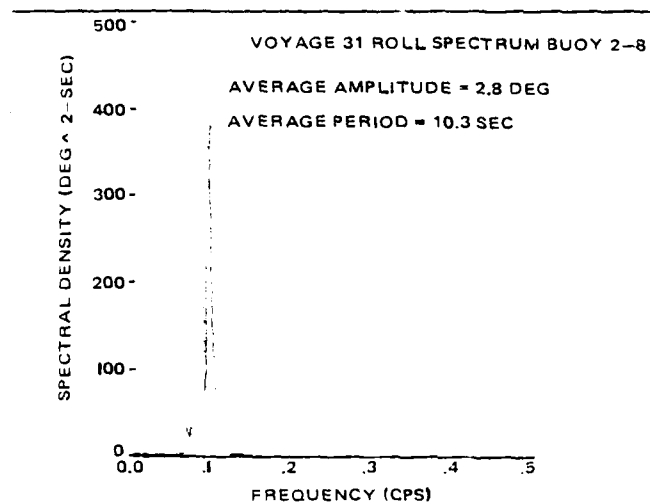
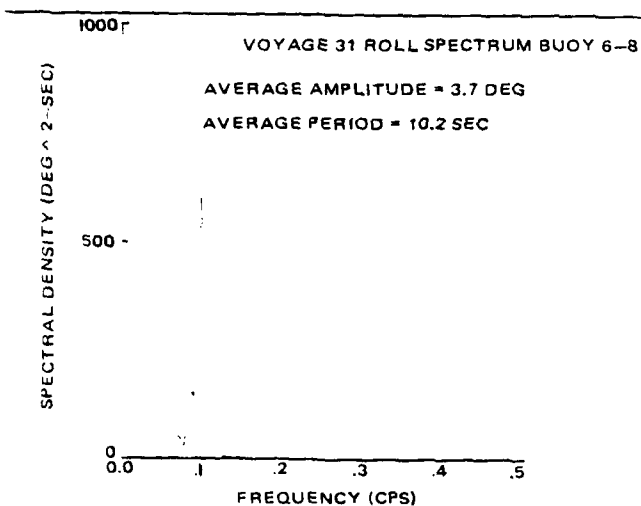
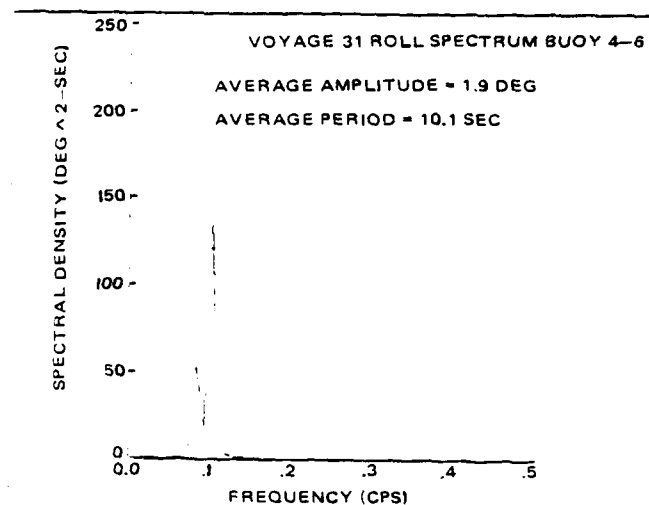
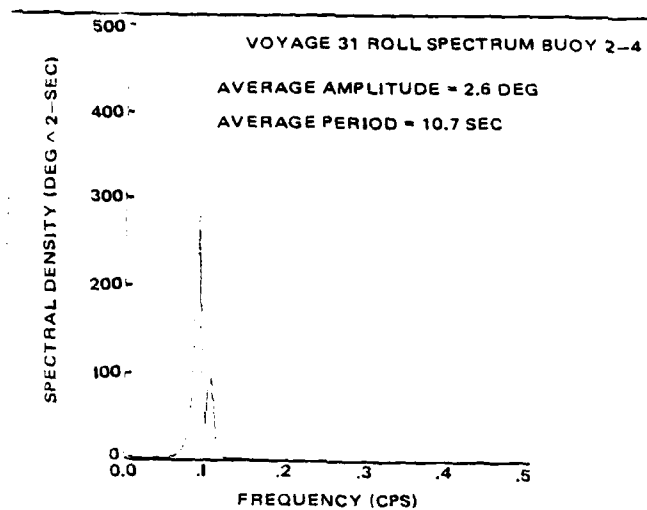


FIGURE 33 ROLL SPECTRA FOR VOYAGE NO. 31

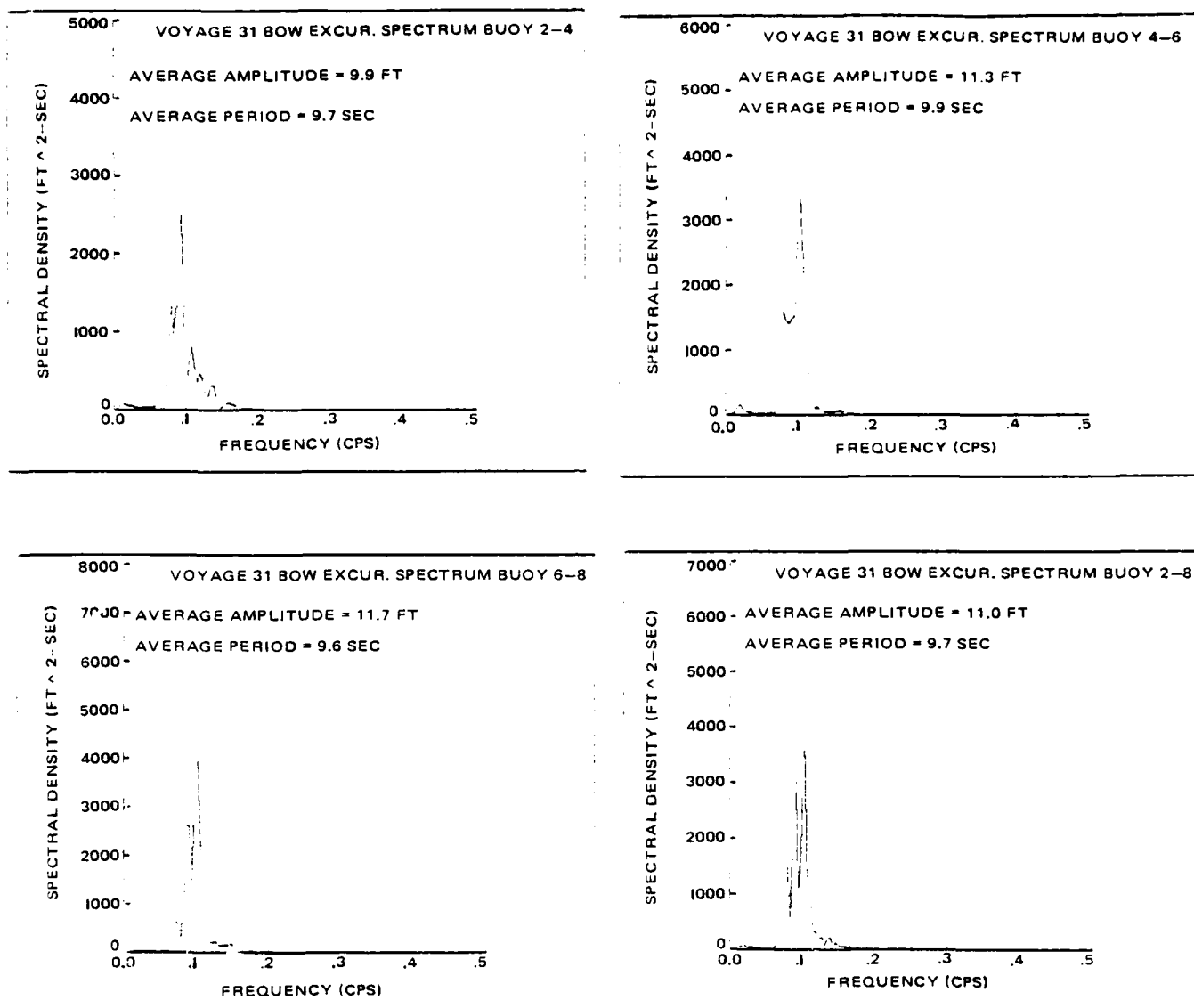


FIGURE 34 BOW EXCURSION SPECTRA FOR VOYAGE NO. 31

TABLE 21a
SUMMARY OF SPECTRAL ANALYSIS ON PITCH DATA

VOYAGE NUMBER	AVERAGE AMPLITUDE (DEG)				AVERAGE PERIOD (SEC)				PEAK PERIOD (SEC)			
	BUOY				BUOY				BUOY			
	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8
15	2.2	2.2	1.8	2.1	16.6	16.6	15.0	16.0	25.0	22.2	20.0	22.2
16	2.5	2.1	2.1	2.2	9.6	9.7	9.5	9.6	11.1	11.2	11.0	11.0
19	1.4	1.6	2.1	1.7	9.7	10.3	10.0	10.0	12.8	11.1	12.6	13.3
20	0.3	0.3	0.5	0.4	8.6	8.7	10.3	9.4	16.7	16.5	17.9	17.9
21*	0.6	0.7	0.8	0.7	11.8	11.0	12.0	11.6	27.8	25.0	20.8	25.0
									15.9	15.6	14.5	16.1
22	0.5	0.6	0.7	0.6	9.9	10.7	12.4	11.2	12.6	12.7	14.5	14.3
30	0.2	0.2	0.2	0.2	7.6	8.3	7.7	7.8	10.5	15.4	8.5	10.5
31	1.3	1.4	1.4	1.4	9.7	9.9	9.6	9.7	10.9	9.5	9.5	9.5
32	0.3	0.4	0.5	0.4	8.0	8.8	9.4	8.9	40.0	25.0	20.0	20.0
33	0.1	0.2	0.1	0.1	7.8	8.2	7.5	7.8	24.4	17.5	20.4	20.2
34	0.5	0.6	0.6	0.6	7.3	7.5	7.7	7.5	6.9	7.8	7.6	8.3
35	1.1	1.0	0.9	1.0	9.0	8.6	8.4	8.7	9.1	8.7	7.7	9.4
36	0.2	0.2	0.3	0.2	7.7	7.9	7.9	7.8	8.3	11.0	8.0	8.0
37	0.2	0.1	0.1	0.2	10.3	8.7	7.4	8.9	27.8	33.3	32.3	28.5
38	--	--	--	--	--	--	--	--	--	--	--	--
39	0.2	0.2	0.2	0.2	7.6	7.1	7.5	7.4	25.0	28.6	30.3	27.0
40	1.1	1.0	1.2	1.1	9.3	9.4	9.8	9.5	11.5	12.1	12.1	12.5
41*	0.1	0.2	0.2	0.2	7.8	7.9	8.0	7.9	40.1	10.9	10.0	10.0
									10.9			
42*	0.2	0.3	0.3	0.3	7.9	9.0	8.2	8.4	19.6	32.4	28.8	29.3
									8.9	7.7	7.7	
43	0.6	0.6	0.5	0.6	4.0	4.6	4.2	4.2	24.9	10.9	29.7	29.7
44	0.9	1.1	1.0	1.0	6.4	7.6	7.9	7.3	9.0	9.0	8.1	8.9
45	0.2	0.3	0.3	0.3	6.4	7.5	6.9	7.0	17.4	24.3	25.6	24.9
46	0.9	0.9	0.9	0.9	5.2	4.5	6.2	5.1	10.0	9.9	9.4	9.9
47	0.3	0.3	0.4	0.3	8.3	8.5	9.5	9.0	32.3	33.3	30.3	30.3
48*	0.4	0.4	0.4	0.4	8.1	8.1	5.9	7.2	20.0	16.7	17.0	20.0
									7.6	7.6	9.1	7.6
49	--	--	--	--	--	--	--	--	--	--	--	--
50	0.8	1.0	0.8	0.9	8.1	9.0	9.1	8.7	11.1	10.4	9.1	10.1
51*	0.5	0.6	0.4	0.5	9.4	9.2	7.6	8.8	25.6	23.5	18.2	25.0
									8.2	8.9	8.2	8.2
52*	0.4	0.5	0.6	0.5	7.6	8.8	7.6	7.8	23.8	30.3	20.0	23.8
									12.2	12.2	10.9	12.2
53*	0.1	0.1	0.2	0.2	6.4	7.5	10.7	8.5	26.3	20.0	24.4	23.8
									9.8		11.1	11.0

* Two major peaks in spectral plot
-- No data due to equipment failure

TABLE 21b
SUMMARY OF SPECTRAL ANALYSIS ON ROLL DATA

VOYAGE NUMBER	AVERAGE AMPLITUDE (DEG)				AVERAGE PERIOD (SEC)				PEAK PERIOD (SEC)			
	BUOY				BUOY				BUOY			
	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8
15	3.7	5.6	4.9	4.8	12.7	13.0	12.0	12.6	10.5	11.1	10.5	10.9
16	4.4	4.7	6.3	5.2	10.9	11.5	11.5	11.2	12.4	12.5	10.9	13.3
19	2.4	4.5	8.4	5.7	13.9	13.6	14.1	13.9	13.9	14.1	14.5	14.7
20	1.6	2.1	3.2	2.6	15.7	15.1	14.6	15.0	16.9	13.9	13.9	13.3
21	4.1	4.4	5.7	4.8	14.7	15.1	15.7	15.3	14.5	14.7	15.4	15.2
22	2.6	3.0	3.3	3.0	13.3	13.6	14.5	13.9	12.8	12.5	14.3	14.3
30	0.4	0.4	0.5	0.5	9.6	11.1	11.1	10.7	9.5	10.9	10.9	10.2
31	2.6	1.9	3.7	2.8	10.7	10.1	10.2	10.3	10.9	9.9	10.2	10.0
32	1.5	1.8	2.1	1.8	16.2	16.9	15.4	16.1	15.4	20.0	14.3	16.1
33	0.4	0.5	0.5	0.5	11.6	14.3	14.7	13.7	11.2	16.8	20.4	22.2
34	0.8	1.2	1.2	1.1	10.5	10.6	11.5	10.9	12.7	12.4	12.5	12.5
35	1.1	1.1	1.0	1.1	12.0	12.5	11.5	12.0	15.4	16.4	17.0	12.8
36	2.0	1.6	1.8	1.8	19.1	19.1	20.7	19.8	17.2	17.0	22.2	18.2
37*	0.3	0.3	0.4	0.3	11.7	9.8	11.5	11.1	24.4	27.0	48.8	32.3
									10.0	10.1	10.1	
38	--	--	--	--	--	--	--	--	--	--	--	--
39	0.5	0.3	0.4	0.4	16.0	10.6	13.3	13.7	9.5	22.7	20.0	20.0
40	1.7	0.9	0.8	1.2	9.8	9.7	9.9	9.8	9.9	9.9	9.8	9.9
41*	1.0	1.2	1.2	1.1	14.4	18.9	17.9	17.1	40.1	50.0	40.1	32.4
									14.3	12.8	12.5	13.0
42	2.3	2.0	2.1	2.2	17.7	18.9	18.8	18.4	17.1	18.4	17.1	16.8
43	0.9	0.9	1.2	1.0	16.3	15.2	15.8	15.7	18.4	17.6	15.4	17.6
44	0.5	1.2	1.4	1.1	12.2	14.2	13.4	13.6	15.2	15.4	16.2	15.4
45	0.7	0.7	0.8	0.8	11.8	11.7	11.5	11.6	11.7	12.0	11.2	11.2
46	0.3	0.4	0.5	0.4	8.7	9.7	9.6	9.4	15.4	12.1	12.5	12.3
47	1.1	6.0	1.7	1.3	16.3	15.9	15.2	15.5	16.7	16.4	16.7	17.2
48	1.6	2.4	2.2	2.1	13.7	14.3	14.4	14.2	14.3	15.6	16.1	14.7
49	--	--	--	--	--	--	--	--	--	--	--	--
50	1.2	1.8	0.9	1.4	10.7	11.0	10.7	10.9	11.1	11.1	11.1	11.1
51	5.5	5.1	4.3	5.0	18.6	17.3	17.2	17.7	20.0	22.7	18.5	20.0
52	1.8	2.0	3.0	2.3	16.6	16.1	16.1	16.2	16.7	16.1	14.9	14.7
53	0.4	0.5	0.8	0.6	10.3	10.9	13.0	11.9	10.8	10.9	11.1	11.1

* Two major peaks in spectral plot
-- No data due to equipment failure

TABLE 21c
SUMMARY OF SPECTRAL ANALYSIS ON BOW EXCURSION DATA

VOYAGE NUMBER	AVERAGE AMPLITUDE (FT)				AVERAGE PERIOD (SEC)				PEAK PERIOD (SEC)			
	BUOY				BUOY				BUOY			
	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8	2-4	4-6	6-8	2-8
15	6.4	6.3	5.7	6.3	10.2	12.4	11.8	11.4	23.3	22.2	20.2	23.3
16	10.5	8.8	9.0	9.5	9.2	9.1	9.0	9.1	11.5	8.3	11.1	11.1
19	5.3	6.4	8.8	7.0	8.6	9.0	8.5	8.6	9.2	11.0	8.4	8.6
20	1.9	2.3	3.9	3.0	8.5	8.6	10.3	9.4	16.9	16.8	17.2	17.2
21*	4.3	4.7	5.6	4.9	11.8	10.9	11.6	11.3	28.7	25.6	23.3	26.3
									16.7	14.9	15.9	16.1
22	3.5	4.2	5.2	4.3	9.9	10.5	12.4	11.1	12.5	14.5	14.7	14.3
30*	1.6	1.8	1.7	1.7	7.3	8.0	7.5	7.6	10.5	14.3	8.3	10.5
											10.9	
31	9.9	11.3	11.7	11.0	9.7	9.9	9.6	9.7	10.9	10.0	9.9	9.7
32	2.4	2.9	3.5	3.0	8.1	8.9	9.4	8.9	33.3	25.0	19.9	20.0
33	1.2	1.4	1.3	1.3	7.6	7.9	7.2	7.6	24.4	18.2	20.8	20.4
34	4.3	4.9	4.9	4.7	7.2	7.4	4.9	7.4	8.4	8.1	7.4	7.8
35	4.4	3.9	4.1	4.1	8.3	8.1	7.8	8.1	8.3	8.9	7.7	7.8
36	1.6	1.6	2.0	1.8	7.3	7.4	7.6	7.4	8.0	14.3	7.7	7.7
37	1.8	1.4	1.3	1.5	10.0	8.7	7.2	8.7	27.0	32.3	32.3	29.4
38	--	--	--	--	--	--	--	--	--	--	--	--
39	0.8	0.8	0.9	0.8	7.0	6.7	7.4	7.1	25.0	30.3	29.4	28.6
40	8.6	8.0	9.1	8.6	9.2	9.2	9.7	9.4	11.5	12.0	13.0	11.8
41*	1.0	1.2	1.5	1.2	7.7	7.8	8.0	7.8	40.1	10.7	10.0	10.0
									10.9			
42	1.1	1.3	1.5	1.3	7.7	9.0	8.0	8.2	19.4	31.8	29.3	28.8
43	2.7	2.4	2.4	2.5	3.9	4.4	4.1	4.1	24.9	25.3	29.7	29.7
44	6.6	7.6	6.7	7.0	5.9	7.1	7.6	6.8	9.0	9.0	8.0	9.0
45	1.1	1.4	1.6	1.4	5.9	7.1	6.7	6.6	17.2	23.6	24.9	24.9
46	8.0	8.3	7.6	8.0	5.1	4.4	5.9	5.0	9.9	9.9	9.5	9.9
47	1.6	1.7	2.4	1.9	8.2	8.3	9.0	8.6	33.3	33.3	30.3	30.3
48*	3.0	2.9	2.8	2.9	8.0	8.2	5.8	7.1	20.0	16.4	17.0	20.0
									7.6	7.6	9.5	7.6
49	--	--	--	--	--	--	--	--	--	--	--	--
50	6.9	8.3	6.3	7.2	7.7	8.6	8.7	8.3	11.1	10.1	9.1	10.1
51	3.3	3.6	2.6	3.2	9.6	9.4	7.5	8.9	25.6	23.8	18.2	25.6
52*	3.2	3.3	4.7	3.8	7.4	8.6	7.5	7.7	23.8	29.4	20.0	23.8
									12.2	12.2	10.9	12.5
53*	0.6	0.7	1.1	0.8	6.0	7.2	9.6	8.0	25.6	18.5	25.0	23.8
									9.4		11.1	11.1

* Two major peaks in spectral plot
-- No data due to equipment failure

TABLE 22
COMPARISON OF AVERAGE AND PEAK PERIODS PROCESSED BY SPECTRAL
METHOD WITH OBSERVED PERIODS OF PITCH AND ROLL MOTIONS

VOYAGE NUMBER	PITCH			ROLL		
	AVERAGE SPECTRAL PERIOD (sec)	PEAK SPECTRAL PERIOD (sec)	OBSERVED PERIOD (sec)	AVERAGE SPECTRAL PERIOD (sec)	PEAK SPECTRAL PERIOD (sec)	OBSERVED PERIOD (sec)
30	7.8	10.5	10	10.7	10.2	10
31	9.7	9.5	10	10.3	10.0	11
32	8.9	20.0	N/A	16.1	16.1	N/A
33	7.8	20.2	N/A	13.7	22.2	15
34	6.9	8.3	8	10.9	12.5	12
35	8.7	9.4	9	12.0	12.8	N/A
36	7.8	8.0	N/A	19.8	18.2	20
37	8.9	28.5	N/A	11.1	32.3/10.1*	N/A
38 Δ	-	-	N/A	-	-	N/A
39	7.4	27.0	N/A	13.7	125.0/20.0*	N/A
40	9.5	12.5	13	9.8	9.9	N/A
41	7.9	10.0	14	17.1	32.4/13.0	11
42	8.4	29.3/7.7*	28	18.4	16.8	18
43	4.2	29.7	18	15.4	17.6	15
44	7.3	8.9	10	13.6	15.4	17
45	7.0	24.9	10	11.6	11.2	15
46	5.1	9.9	8	9.4	12.3	10
47	9.0	30.3	14	15.5	17.2	15
48	7.2	20.0/7.5*	12	14.2	14.7	14
49 Δ	-	-	N/A	-	-	14
50	8.7	10.1	11	10.9	11.1	14
51	8.8	25.0/8.2*	15	17.7	20.0	16
52	7.8	23.8/12.2*	18	16.2	14.7	14
53	8.5	23.8/11.1*	18	11.9	11.1	13

* Two major peaks in spectral plot

Δ No spectral data due to equipment failure

is calculated from the spectral density function $s(f)$ by

$$\bar{T} = \left[\frac{\int_0^{\infty} s(f) df}{\int_0^{\infty} s(f) f^2 df} \right]^{\frac{1}{2}} \quad (24)$$

It appears in general that the observed values agree more with the peak spectral periods than the average periods.

The average response amplitudes presented in Table 21 are obtained based upon the assumption that the spectra are narrow-banded and thus the Rayleigh law of distribution applies. These values compared with those processed from the method of time history are presented in Table 23. The good agreement shown through these tabulated values indicates further that vessel motions in the channel are approximately Rayleigh distributed as discussed in Section 7.

9.2 WAVE SPECTRA

Wave measurements and the radar image system were started in the latter part of the Phase I study and continued for the entire Phase II study. All data are to be processed by the U.S. Army Coastal Engineering Research Center. The processed data which are available to this project are summarized in Table 24. Plots of wave spectra for those voyages are included in Appendix G. Wave data for Voyage Nos. 20, 21, 22, 30 and 31 were obtained from a Waverider buoy near the lightship. The remaining wave data were obtained from wave gauges which were installed in the Coast Guard navigational lightbuoy which replaced the lightship. All wave measurements were made in deep water relative to the channel depth. The observed wave heights and periods, also near the lightship, are included in the table for comparison.

TABLE 23
COMPARISON OF AVERAGE AMPLITUDES PROCESSED BY SPECTRAL
METHOD WITH THAT OBTAINED FROM TIME HISTORY

VOYAGE NUMBER	PITCH AMPLITUDE (DEG)		ROLL AMPLITUDE (DEG)		BOW EXCURSION AMPLITUDE (FT)	
	FROM SPECTRUM	FROM TIME HISTORY	FROM SPECTRUM	FROM TIME HISTORY	FROM SPECTRUM	FROM TIME HISTORY
15	2.1	1.9	4.8	4.4	6.3	6.0
16	2.2	2.2	5.2	5.1	9.5	9.5
19	1.7	1.7	5.7	4.4	7.0	6.9
20	0.4	0.4	2.6	2.7	3.0	2.5
21	0.7	0.8	4.8	5.1	4.9	4.4
22	0.6	0.6	3.0	3.1	4.3	4.2
30	0.2	0.3	0.5	0.5	1.7	1.3
31	1.4	1.5	2.8	2.8	11.0	11.2
32	0.4	0.5	1.8	1.8	3.0	2.9
33	0.1	0.2	0.5	0.5	1.3	1.2
34	0.6	0.6	1.1	1.1	4.7	5.0
35	1.0	1.1	1.1	1.1	4.1	4.6
36	0.2	0.3	1.8	1.9	1.8	0.3
37	0.2	0.3	0.3	0.4	1.5	1.2
38Δ	--	--	--	--	--	--
39	0.2	0.2	0.4	0.4	0.8	0.7
40	1.1	1.0	1.2	0.8	8.6	7.9
41	0.2	0.2	1.1	1.2	1.2	1.0
42	0.3	0.3	2.2	2.2	1.3	1.3
43	0.6	0.4	1.0	1.0	2.5	1.6
44	1.0	1.0	1.1	1.1	7.0	9.5
45	0.3	0.3	0.8	0.9	1.4	1.4
46	0.9	0.7	0.4	0.5	8.0	6.8
47	0.3	0.4	1.3	1.6	1.9	2.0
48	0.4	0.5	2.1	2.0	2.9	2.9
49Δ	--	--	--	--	--	--
50	0.9	0.8	1.4	1.4	7.2	5.9
51	0.5	0.5	5.0	5.5	3.2	2.4
52	0.5	0.7	2.3	2.6	3.8	3.8
53	0.2	0.3	0.6	0.6	0.8	0.8

Δ No data due to equipment failure

TABLE 24
SUMMARY OF WAVE SPECTRA DATA AND OBSERVED WAVE DATA

VOYAGE NUMBER	SPECTRAL DATA ⁺		OBSERVED DATA	
	SIGNIFICANT WAVE HEIGHT (ft)	PEAK SPECTRAL WAVE PERIOD (sec)	WAVE HEIGHT (ft)	WAVE PERIOD (sec)
20	9.6	12.3	10-12	10-11
21	13.6	14.1	10	8-10
22	10.1	10.8	10-12	10
30	3.8	10.8	5	8
31	9.0	14.1	8-10	8
32 Δ	-	-	6-8	10
33	3.9	8.3	2-4	10
34	7.2	9.1	6	9
35	9.8	12.5	6-8	8-10
36	7.4	8.3	3-6	8
37	7.8	12.5	6-8	10
38	12.6	7.7	6-10	6-7
39	4.3	9.1	4-6	8
40	12.9	11.1	8	8
41	4.0	16.7	3-5	8-10
42	5.3	11.1	6-8	13
43	7.5	12.5	6-8	10
44	14.3	11.1	10-15	8
45	5.5	12.5	4-5	10
46 Δ	-	-	4-6	8-10
47	6.3	14.3	6-8	8-10
48	7.9	6.3	2-4	8-9
49	9.6	12.5	4-6	13
50	8.0	14.3	8-10	12-13
51	9.9	14.3	6-8	6-8
52 Δ	-	-	8-10	12
53 Δ	-	-	2-4	9-10

⁺ Data provided by U.S. Army Coastal Engineering Research Center
 Δ Spectral data unavailable for these voyages

The environmental conditions at the Columbia River Entrance are known to be severe from the standpoint of vessel operations. Strong currents which set across the entrance channel alignments, impaired visibility during the late summer through winter months, and high wind and wave conditions associated with winter storms create a navigational environment which requires considerable judgment and caution on the part of the mariner.

During the period of the project field operations, however, the conditions at the river entrance were not as severe as was expected. Out of 29 bar crossings in the first phase from May 1978 through March 1979, 21 were rated "easy" by the pilots. Of the remaining eight crossings, six were rated "moderate" and two "difficult". The conditions during the second phase from October 1979 to April 1980 were considerably rougher in terms of winds and waves. However, because the channel is not open for ship traffic in wave conditions which exceed a certain limit, regulated by the pilots, and the random nature in which vessels were selected for monitoring the measurements obtained in Phase II are in fact not significantly different from those of Phase I. Of the 24 bar crossings in the second phase, 20 were rated "easy", four "moderate", and none "difficult".

The environmental parameter which distinguished the "moderate" and "difficult" crossings was swell height, which began to adversely affect vessel navigation when it reached about 10 ft. It seems plausible that seas of this magnitude would also exert a significant negative influence when encountered. When wave heights were less than 10 ft, the other environmental factors such as visibility and currents appeared not to pose a major obstacle to vessel use of the entrance channel. When high wave conditions were present, however, the other factors assumed an increased importance in rendering safe navigation difficult, or, in some cases, impossible.

An additional factor affecting the difficulty of crossings was the vessel draft. The pilots exercised greater caution when bringing deep-drafted vessels across the bar in rough conditions to prevent grounding. A first precautionary measure was to reduce speed, while in more extreme wave conditions, vessels exceeding a certain draft were not permitted to cross the bar. These measures were generally applied at the discretion of each individual pilot.

A total of 18 ships were utilized in the project. These ships have a design draft ranging from 29 to 37 ft, representing the deeper-draft vessels which frequent the channel. Categorically these 18 vessels belong to four groups--oil carriers, container carriers, bulk carriers and auto-carriers. Whereas the vessel characteristics are not identical among these four groups of ships, they fall into the same approximate length class and their response behavior is not significantly different.

Analyses of the data obtained from all 53 recordings have been conducted. In these analyses, no effects of ship form or characteristics are considered as they are of less significance than other parameters. In general, the data show that the dominant factor affecting vessel motions is wave conditions. However, wind, current and weather conditions may further hinder the safe navigation of the entrance channel when the wave conditions are sufficiently severe. Additionally, ebb tide currents known to mariners who frequent the channel, worsen wave conditions and pose a major problem to vessel navigation. However, they were observed to affect vessel operations only when the incoming waves reach 10 ft or higher. Under the influence of a strong ebb current, offshore waves with a height in excess of 10 ft may begin to break in portions of the entrance channel.

The predominant swell directions recorded were between northwest and west. Under these wave conditions, the inbound vessel follows a quartering stern sea whereas the outbound vessel

heads into a quartering bow sea. Consequently, a vessel experiences higher vertical responses in outbound voyages than inbound voyages when the wave length is approximately on the order of the ship length. (The average period of the waves observed in this study is 9 seconds, and the corresponding wave length is approximately 400 ft in deep water).

An effort to analyze the measured data statistically has also been tried. The results of the analysis may be summarized as follows:

1. Statistical analyses of the measured data show that there is no significant difference between the Phase I and Phase II data, although the environmental conditions were not the same. The data collected from the second phase program, therefore, provide additional support to the results derived from the first phase study. Since all ship transits are subject to an inherently regulated environmental criterion, the bar closure, the combined data seem sufficient to provide representative statistics, although the environmental conditions of both years monitored are not representative of typical winters.
2. Considering the data from each voyage independently, the frequency distributions of pitch, roll, heave and the vertical motions at various locations of a vessel have been shown to follow the Rayleigh law of distribution. Consequently, significant vessel motions for a particular transit can be predicted with confidence, if the characteristics of vessel response with respect to environmental parameters are known.
3. Assuming the 18 ships monitored in the project to behave equally and allowing the environmental conditions to vary over a range that the ships may encounter, a long term statistical pattern of the transit vessel motions has

been investigated based upon the measured data. The analysis shows that the vertical vessel motions appear to be logarithmically normal distributed. As indicated by the distribution diagram (Figure 21), on the basis of duration the probability for all vessels over all transits to exceed a 15-ft vertical excursion is about 1%.

4. From extreme value analysis, it is shown that there is a 90% probability that a given transit may experience a vertical excursion of up to 23 ft*. It is understood that this probability is described in terms of voyage or transit rather than duration, as used previously. Similarly, the maximum vertical penetration of a vessel is predicted to be 53 ft based on a 90% probability.
5. The maneuvering lane width is governed by the vessel controllability and maneuverability as well as the weather and wave conditions encountered in the channel. Analysis of the measured data available in 40 of the 53 voyages shows that the average lane width calculated is 410 ft, with a standard deviation of 195 ft. This result indicates the vessel maneuvering width to be 730 ft based on a 90% probability.
6. The results that short term observations follow the Rayleigh law of distribution and long term data are distributed log-normally indicate that ship motions in the channel are essentially linear. This conclusion applies at least to the case of channel depth/draft ratios ranging from 1.6 to 2.6, the range covered by the present data. Consequently, it can also be concluded that the application of systematic analysis of vessel motions through linear, analytical methods should provide a convenient, valid procedure for channel design, and be of great usefulness to the overall program on navigational channel development.

* This is equivalent to saying that the probability to exceed a 23 ft vertical excursion is 10%.

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